Measurement of Radiative Capture Reactions Using Radioactive Beams: Opportunities for Surrogate Reactions

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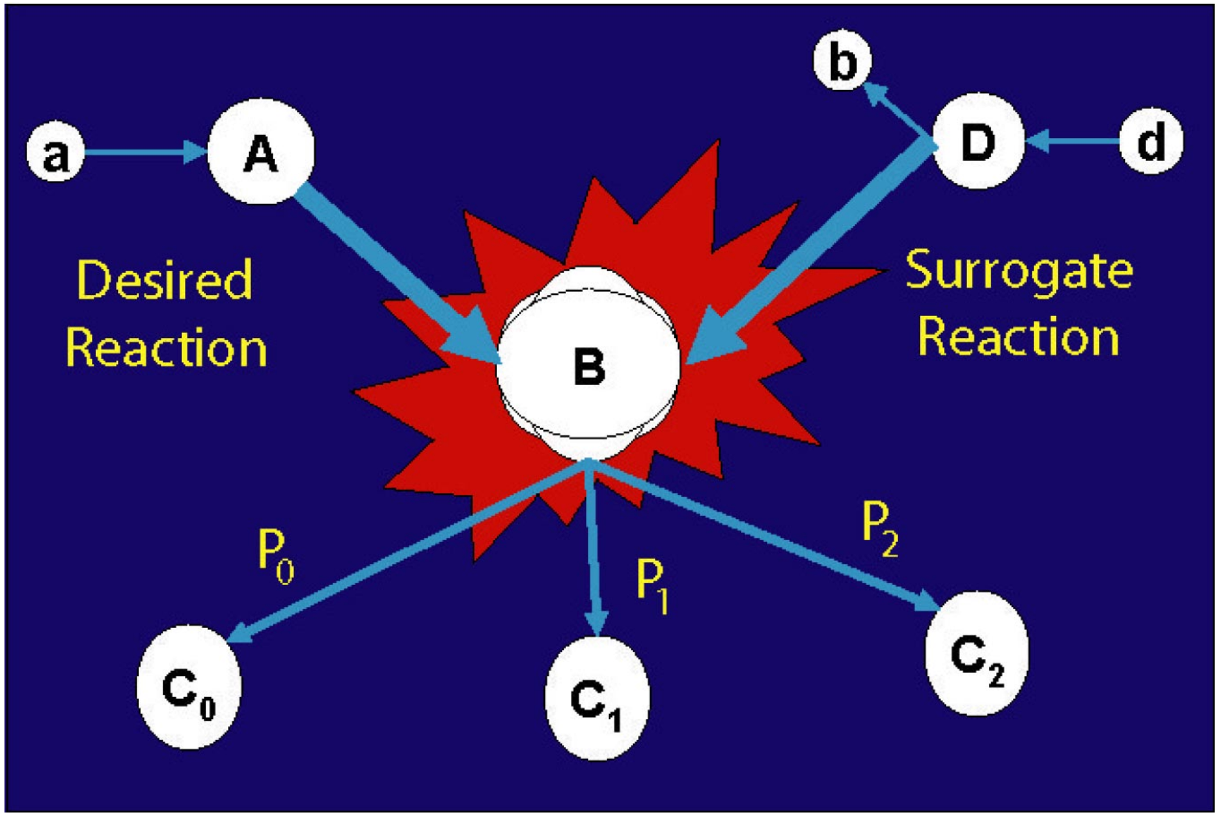
Nuclear Reactions on Unstable Nuclei
and the Surrogate Reaction Technique
Workshop 2004



To study certain nuclear parameters involving exotic nuclei will require radioactive beams.

What can we expect to do DIRECTLY with radioactive beams given today's facilities
And what are the limitations → opportunities for surrogate or indirect studies.

These opportunities can involve radioactive and stable heavy ion beams.

Let's consider radiative capture reaction rates, i.e., proton, alpha, heavy ion capture.
(neutron capture is an obvious opportunity for surrogate reactions)

Outline of Talk

- Why (radiative capture involving exotic nuclei) ?
  - Nuclear astrophysics
- How directly?
  - Inverse kinematics using DRAGON
  - What do we need to know before starting?
- Examples (at ISAC using DRAGON)
  - ^{21}Na(p,γ)^{22}Mg; ^{26}Al(p,γ)^{27}Si; ^{15}O(α,γ)^{19}Ne; ^{12}C(α,γ)^{16}O
- Capabilities of RB Facilities Today
- Opportunities for Surrogate Reaction Studies
- Comments

“We are all nuclear debris”
Willie Fowler, 1985

Role of Nuclear Astrophysics

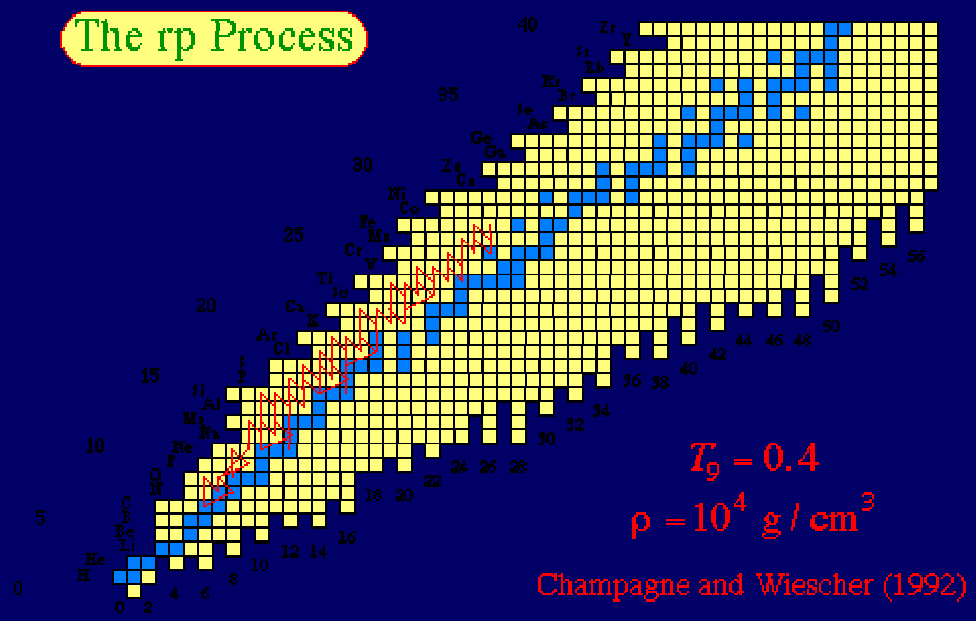
- Nucleosynthesis in stars
- Energy generation in stars

How: Many ways including studies of simple nuclear reactions at low energies using appropriate accelerators

“We stand on the verge of one of those exciting periods which occur in science from time to time. In the past few years, it has become abundantly clear that there is an urgent need for data on the properties and interactions of radioactive nuclei…..for use in **nuclear astrophysics**……At the same time methods for producing radioactive and isomeric nuclei, and for accelerating them in sufficient quantities have been proposed and even brought to the design stage with estimates for performance and cost….**Let’s get on with it!”**

Willie Fowler, Parksville, 1985

rp-process



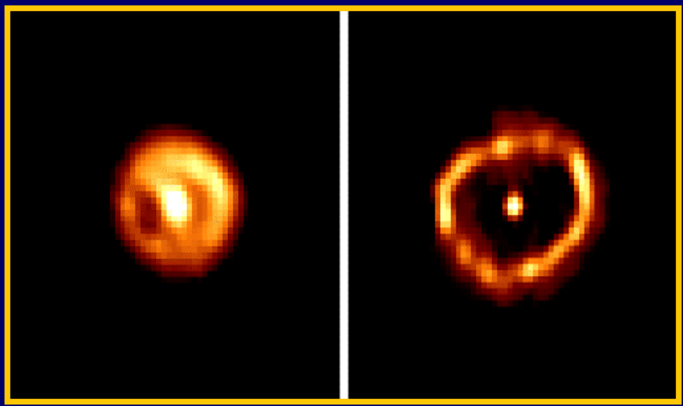
- Series of (p,γ) and (β^+,ν_e) steps, inhibited by (p,α)
- Rapid processes
- Involves radioactive reactants
- Hydrogen-rich environment required
- Hot (Coulomb barriers to penetrate)

Candidates: Novae, Supernovae, X-ray binaries

Nuclear Astrophysics at ISAC with DRAGON and TUDA

Explosive Astrophysics Sites

Nova Cygni Erupted 2/92



Left 5/93 Right 6/94

- Novae, X-ray bursters, supernovae type 1a
- Binary system – compact object (white dwarf or neutron star) and main sequence or red giant star

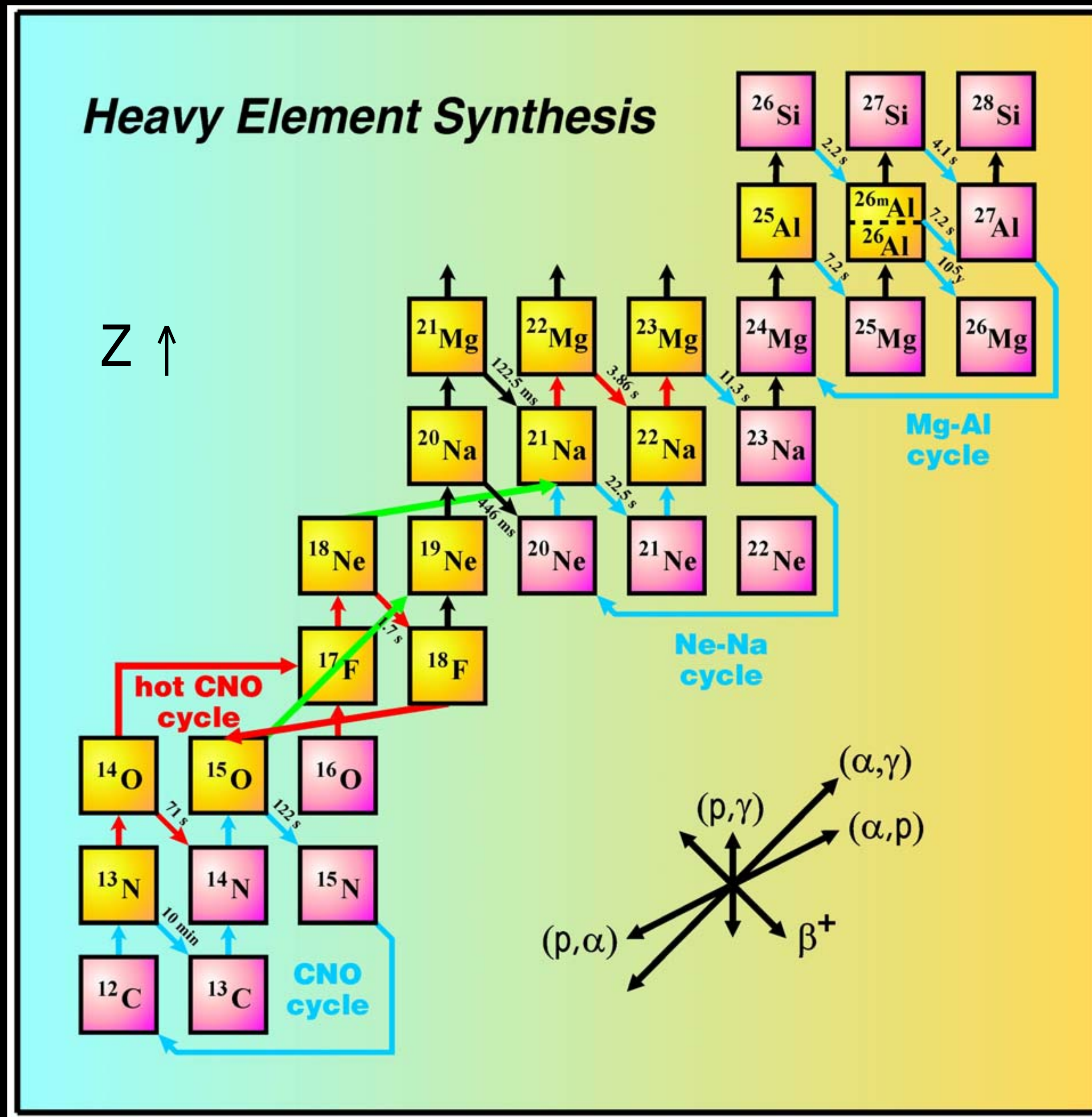
ONeMg NOVA

- Accretion of hydrogen rich material on surface of white dwarf that had C burning
- Thermonuclear runaway – lots of energy
- High temperatures and short timescales

Radioactive nuclei important

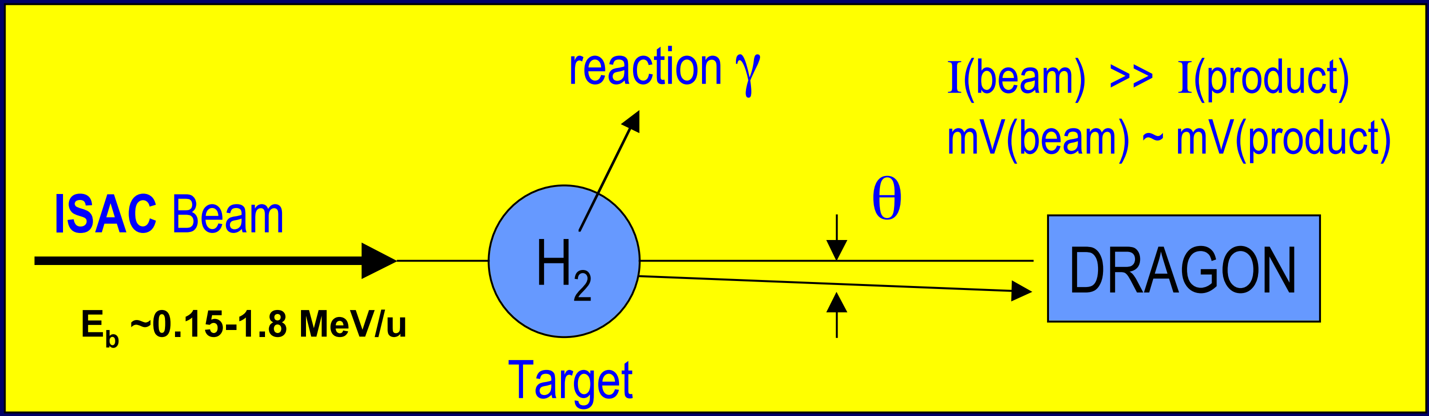
DRAGON designed for radiative proton and alpha reactions with **radioactive and stable beams**

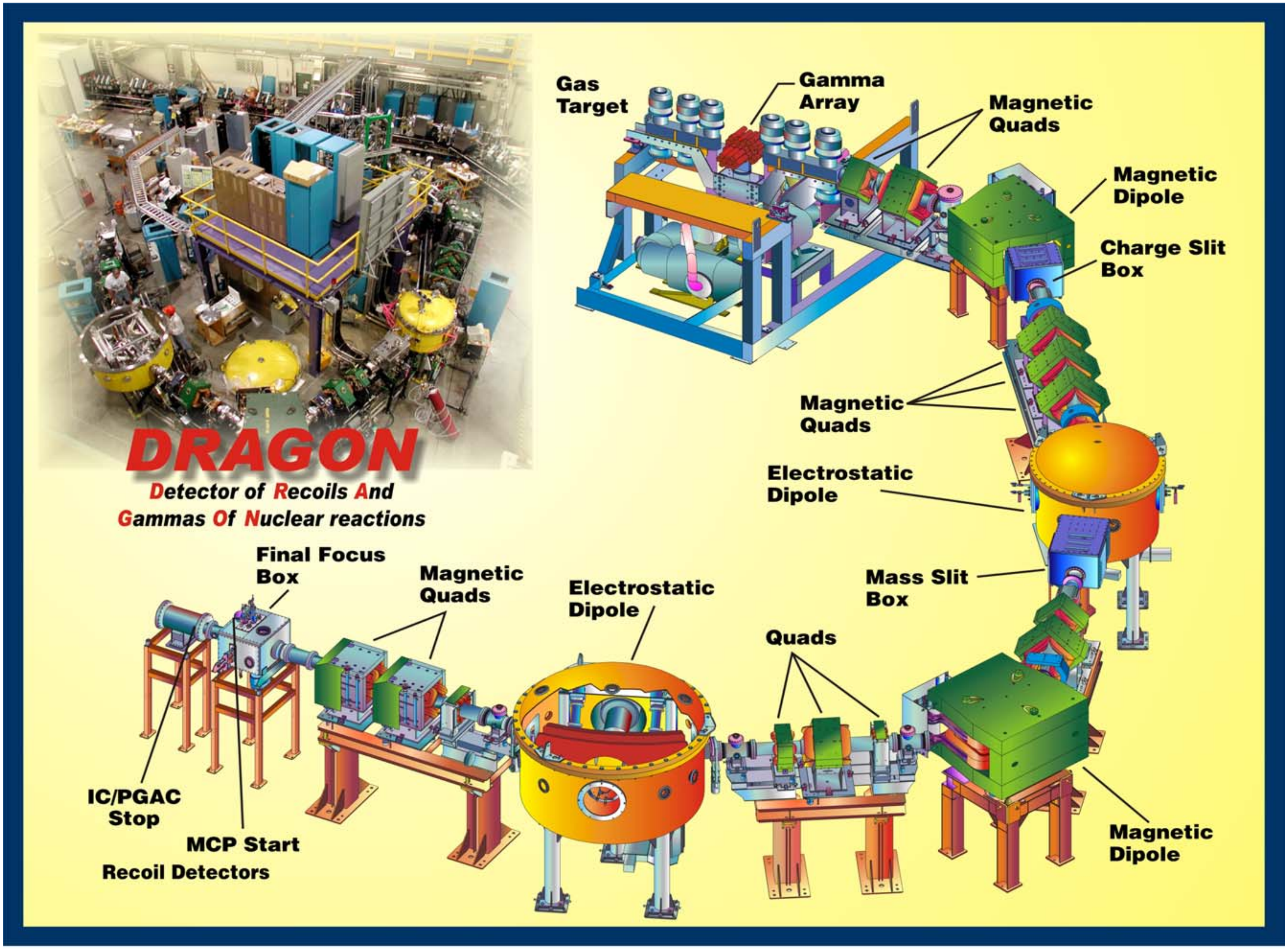
TUDA designed for particle reactions


Heavy Element Synthesis
Z ↑
26Si 27Si 28Si
25Al 26mAl 26Al 27Al
21Mg 22Mg 23Mg 24Mg 25Mg 26Mg
20Na 21Na 22Na 23Na
18Ne 19Ne 20Ne 21Ne 22Ne
17F 18F
14O 15O 16O
13N 14N 15N
12C 13C
2.2 s
4.1 s
7.2 s
7.2 s
105y
122.5 ms
3.86 s
11.3 s
22.5 s
446 ms
1.7 s
71 s
122 s
10 min
hot CNO cycle
CNO cycle
Ne-Na cycle
Mg-Al cycle
(α,γ)
(p,γ)
(α,p)
(p,α)
β+

Goal of DRAGON Program

- Direct measurement of the rate of radiative proton and alpha capture reactions involving primarily exotic radioactive reactants but also stable isotopic reactants (as beams)
- Approach: Inverse kinematics




DRAGON
Detector of Recoils And
Gammas Of Nuclear reactions
Gas Target
Gamma Array
Magnetic Quads
Magnetic Dipole
Charge Slit Box
Magnetic Quads
Electrostatic Dipole
Mass Slit Box
Quads
Magnetic Dipole
Electrostatic Dipole
Magnetic Quads
Final Focus Box
IC/PGAC Stop
MCP Start
Recoil Detectors

Features of DRAGON

- DRAGON is ~20 m long; 1-4 μs in flight path depending….
- DRAGON acceptance is <~± 20 mrad; ± 4% in energy
- Gas target operates <~ 8 torr (H_2 and He)
- BGO Gamma Array efficiency ~ 50% depending….
- EMS limitations: electric rigidity = 8 MV (2E/q);
  magnetic rigidity = 0.5 T-m [m/q $(2E/m)^{1/2}$]
- EMS accepts only one charge state
- Beam transmission/suppression depends on energy (total < 10^{-15})
- Focal plane detector
  - DSSSD (Double sided, Si strip detector)
  - Ionization chamber (someday with a PGAC)
  - Both detectors can be operated with a MCP/C foil system for fast signal

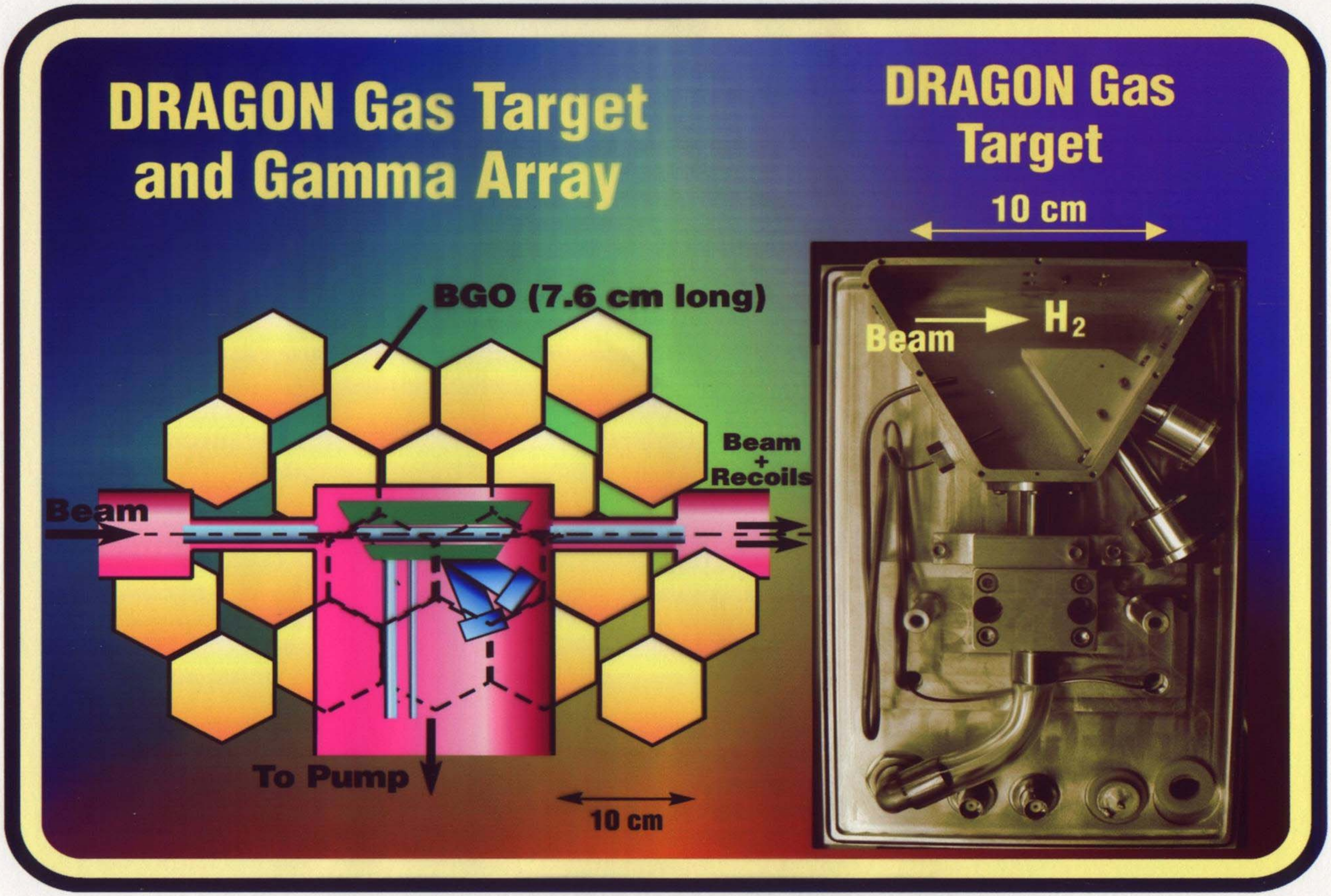
Direct Studies of Radiative Capture

Experimental Challenges Using Radioactive Beams

- Beam intensities much less than stable beams (if available at all).
- Cross sections are small (resonance strengths ~ 1 meV) .
- Beam is radioactive (background radiation, e.g., 511 keV γ, ~10^9/s)
- Radiative proton and helium capture requires gas target.

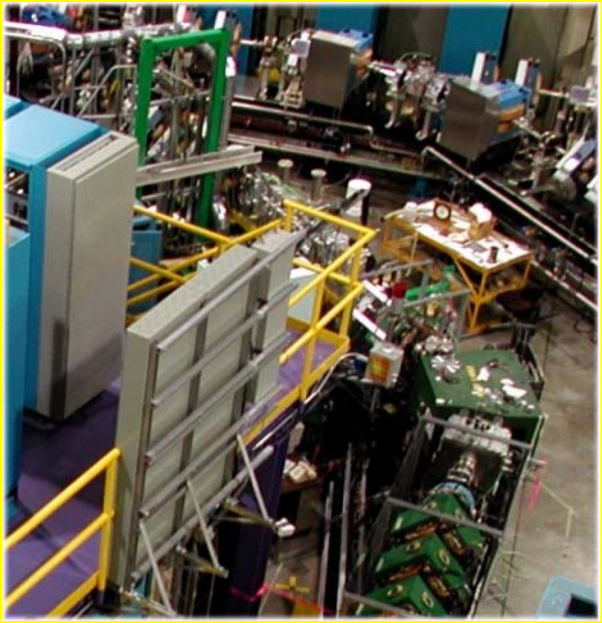
- What do you need to know before starting ?
  - Resonance energy (thickness of gas target ~ 14 keV)
  - Radioactive beam energy (different RB accelerators)
  - Accurate beam intensity (and reaction product yield)
  - Resonance width and gamma branching ratio useful
  - Angular spread of the recoils in inverse kinematics
  - Charge state distribution important

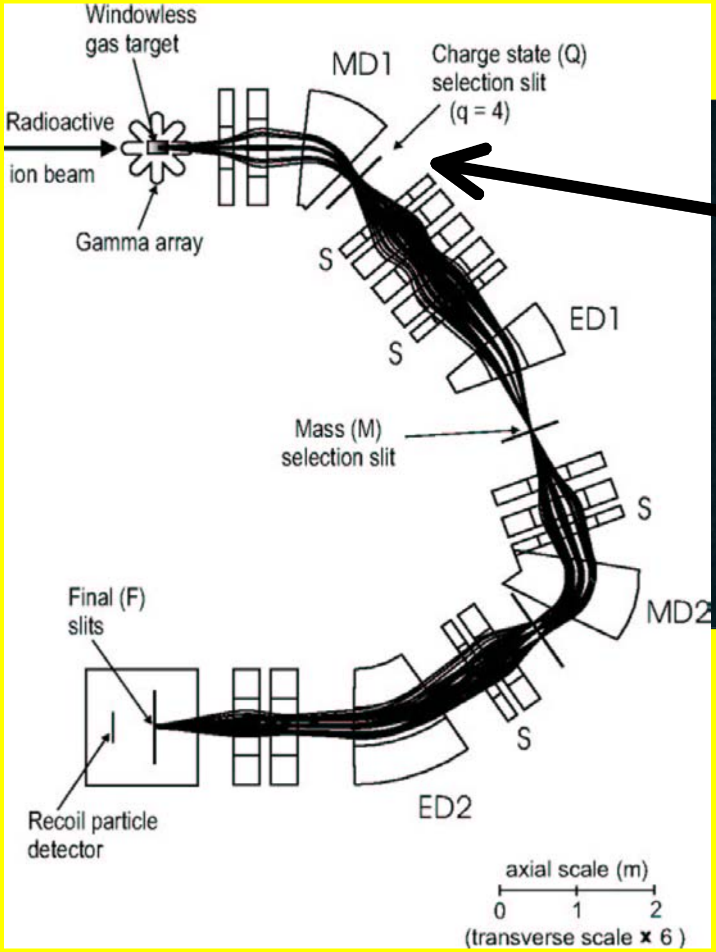
- What do you measure [Quantitative measurement to ± 20%]
  - Thick Target Yield = _ _^{2} ___(1/ _) $(M_b + M_t)/(M_t)$ (for narrow resonance)
  - Need to do full scan for broad resonances

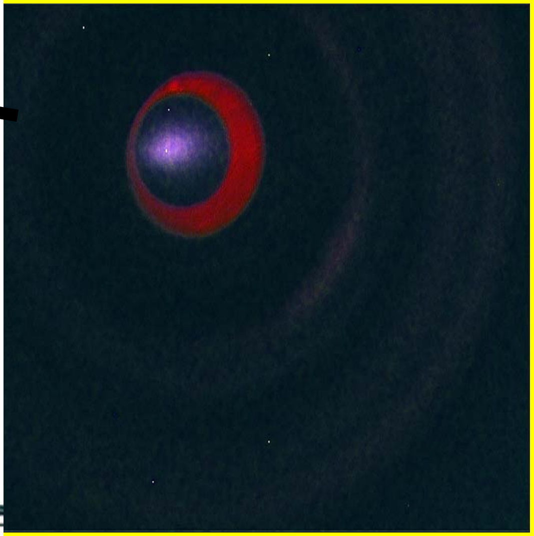


windowless, recirculating, differentially pumped

Eye of the DRAGON







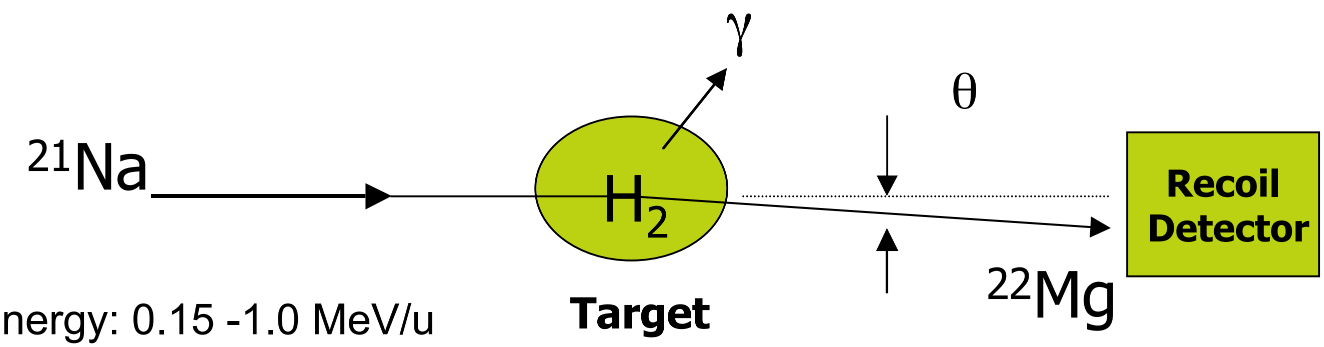
$^{21}Na(p,\gamma)^{22}Mg$

$^{1}H(^{21}Na,^{22}Mg)\ \gamma$

Basic Experimental Approach

$^{21}Na + p \longrightarrow {}^{22}Mg + \gamma$

Inverse kinematics



Beam energy: 0.15 -1.0 MeV/u

Advantage: $\theta <\sim 1$ deg, could accept all recoils

Challenges: Beam and recoil have ~same momentum.
Rate of beam >>> rate of recoils ($10^{11}/1$).
Beam is radioactive leading to background.

Requires: Intense source of radioactive ^{21}Na - ISAC
Efficient detection of ^{22}Mg
Very efficient rejection of ^{21}Na
Windowless hydrogen gas target

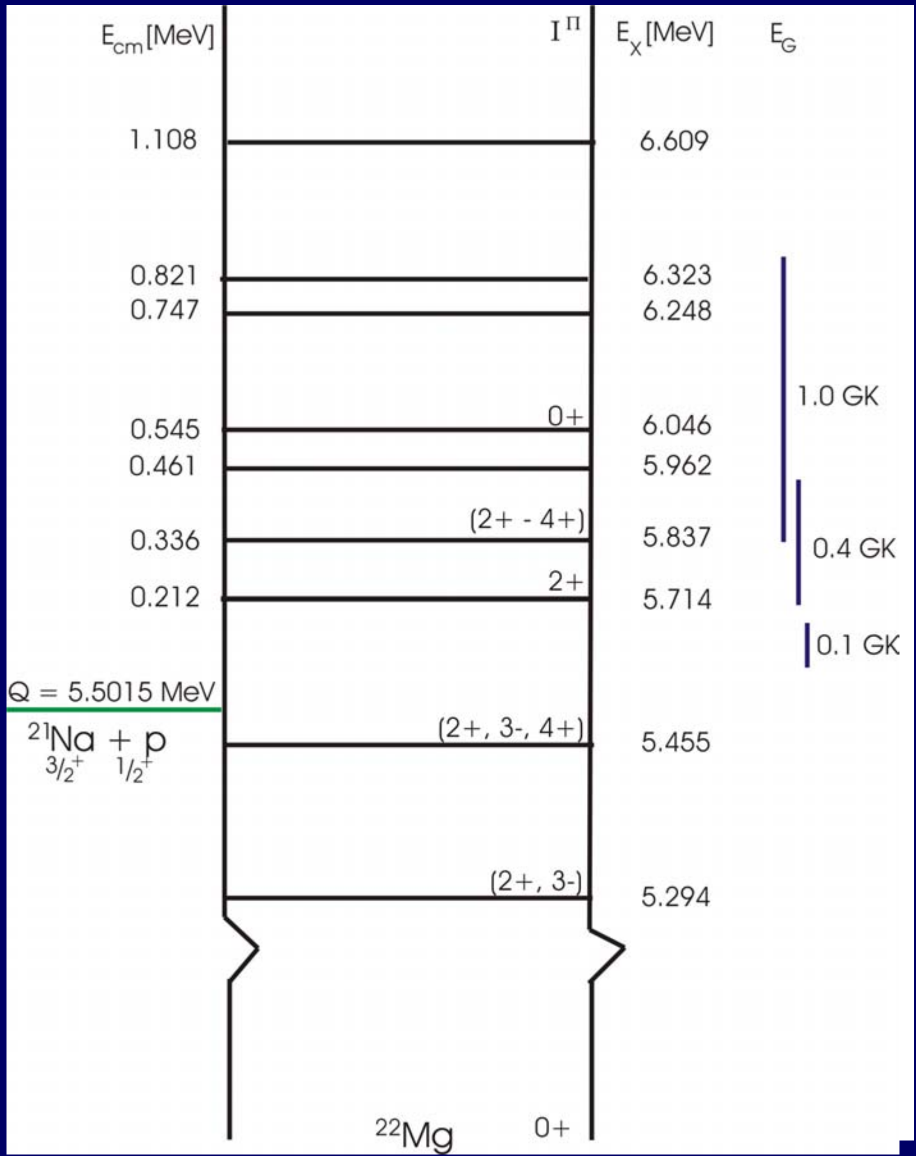
DRAGON

$^{21}Na(p,\gamma)^{22}Mg$

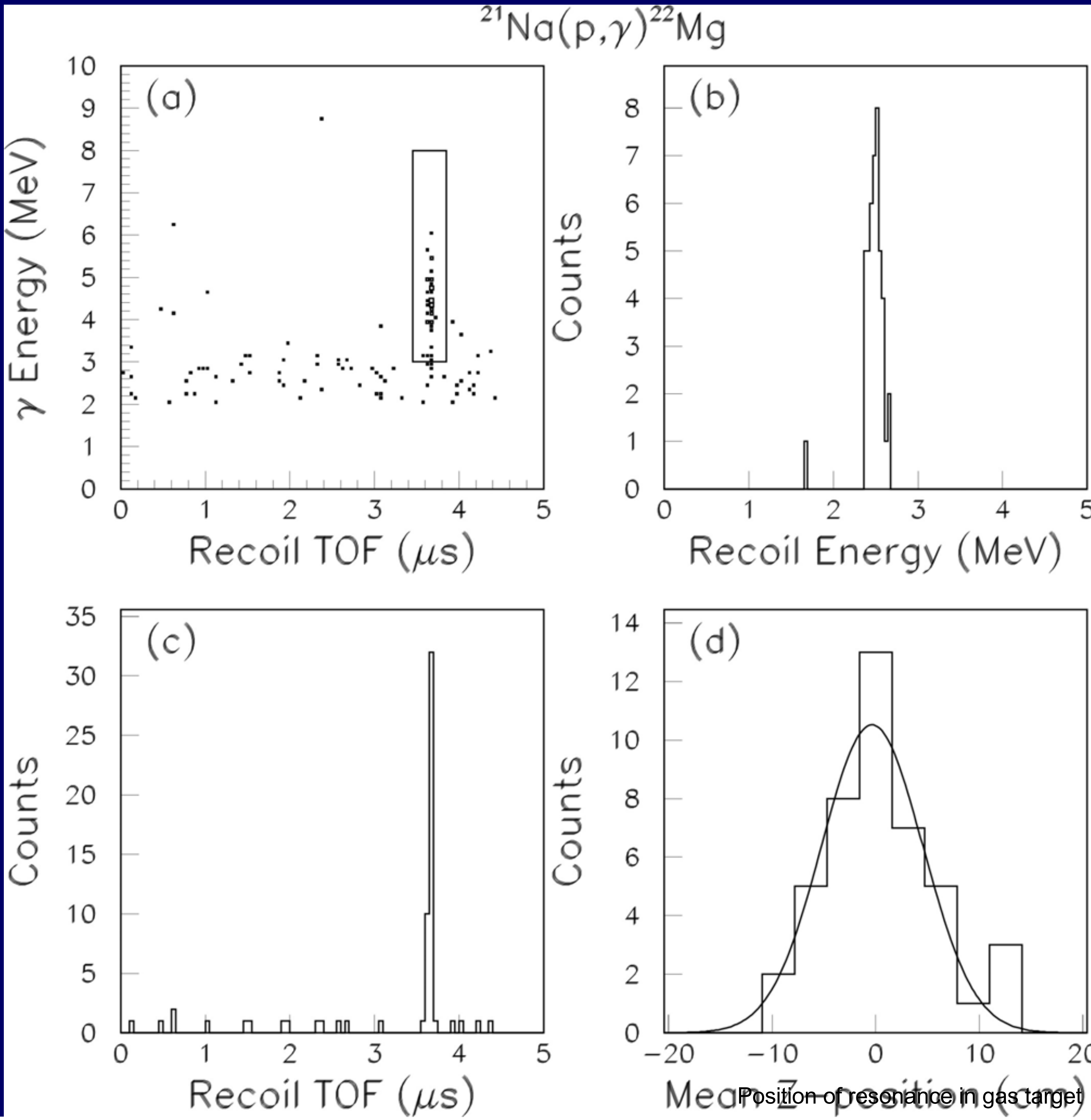
Proton capture on ^{21}Na dominated by isolated narrow resonances at T ~ 0.4 GK.

Knowledge of energy levels initially based on:
* transfer reactions,e.g.(p,t),(^{3}He,n)
* isospin mirror nucleus ^{22}Ne

Levels of ^{22}Mg



BGO-DSSD coincidence
Prompt γ – recoil coin.

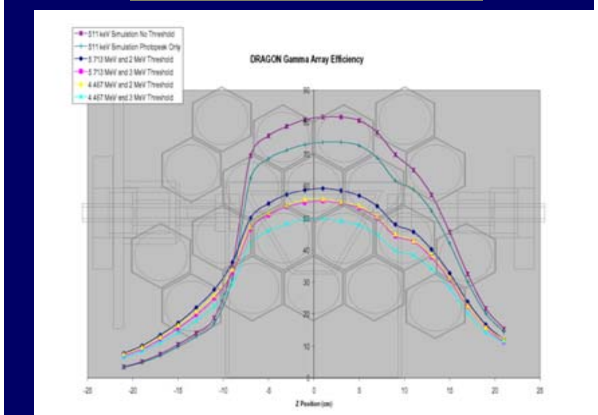


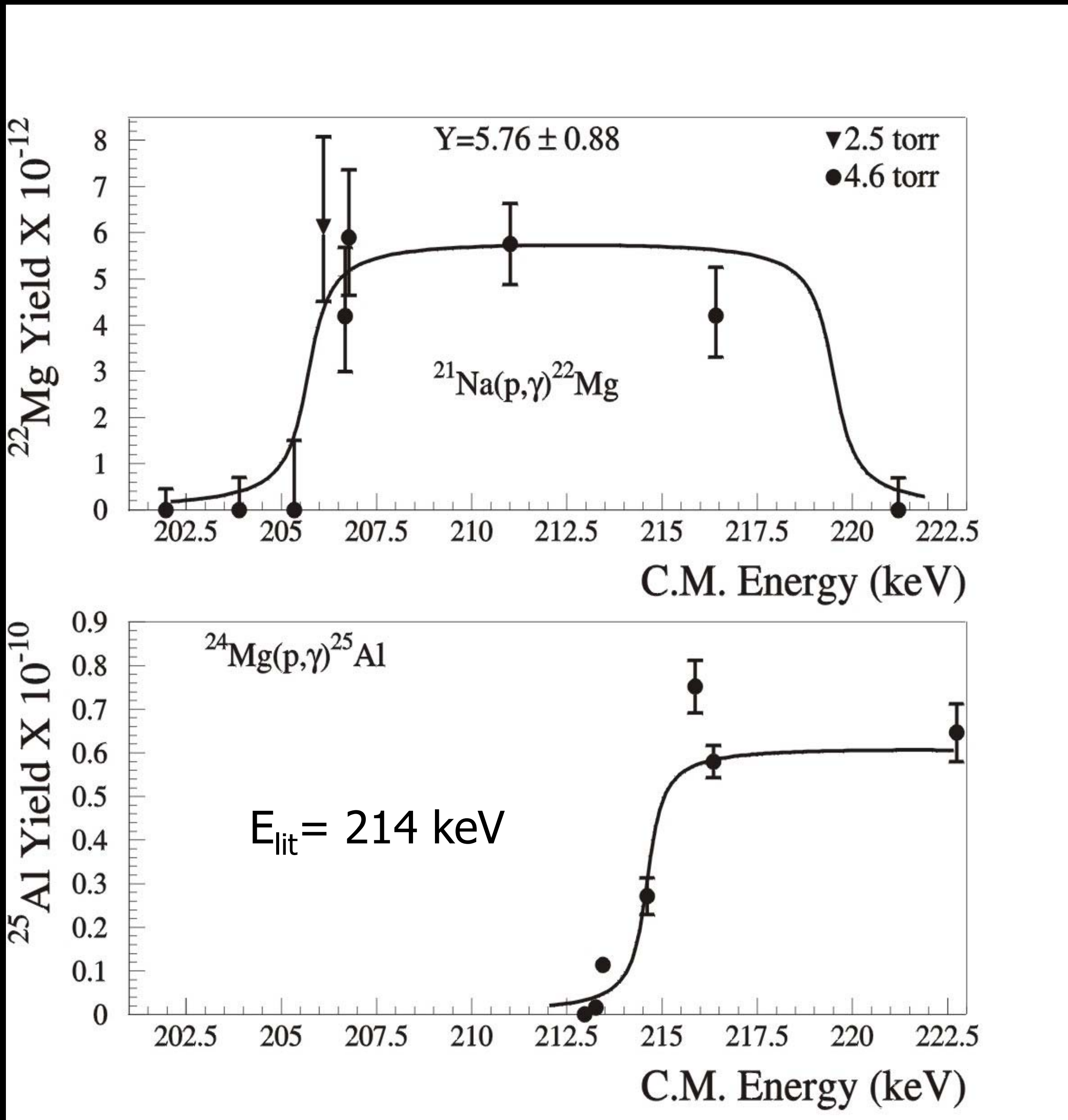
Position of resonance in gas target

E_{beam} = 220 keV/u
$E_{c.m.}$ = 212 keV
$I(^{21}Na) \leq 2 \times 10^9\ s^{-1}$

~ 1 count per hour

BGO Efficiency





Results for '212' Resonance

Thick target yield
-only mid point used
$\omega\gamma$=1.03±0.16±0.14 meV

Resonance energy
E_{cm} = 205.7±.5 keV

Not 212 keV

Why?

Mass of ^{22}Mg
= -403.2±1.3 keV

Not –396.8 keV

PRL 90 (2003)162501

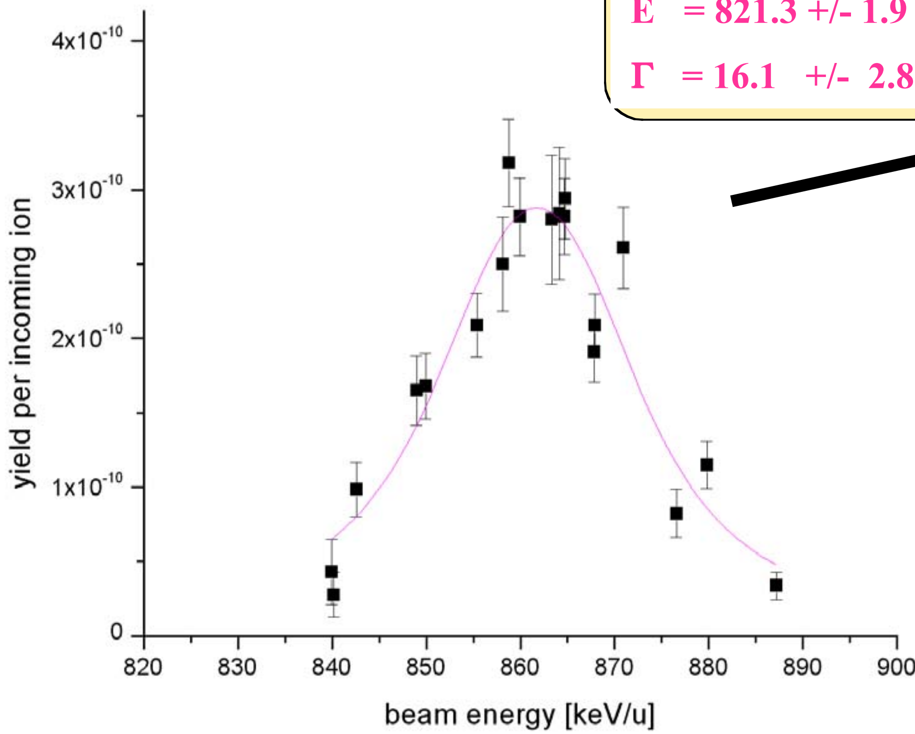
Results from a broad resonance

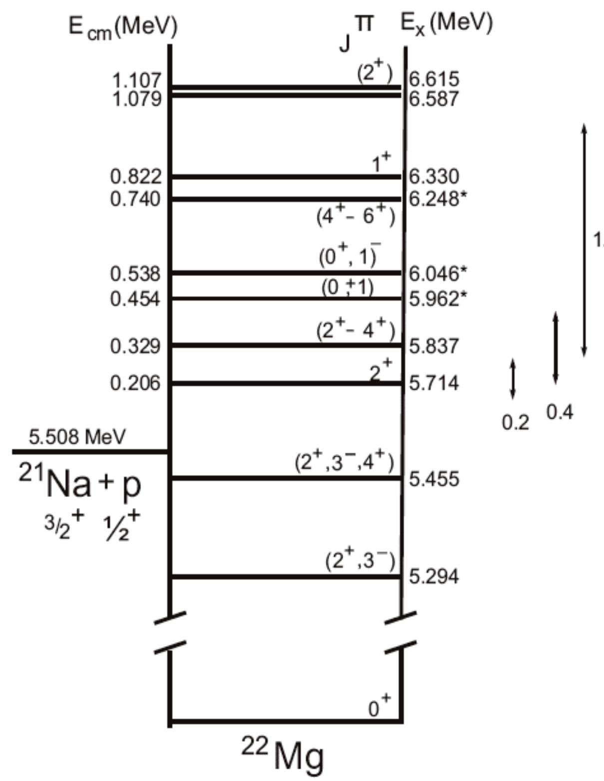
$^{21}Na(p,\gamma)^{22}Mg$ at E_{cm} = 821 keV

$\omega\gamma$ = 556 +/-77 meV

E = 821.3 +/- 1.9 keV

Γ = 16.1 +/- 2.8 keV

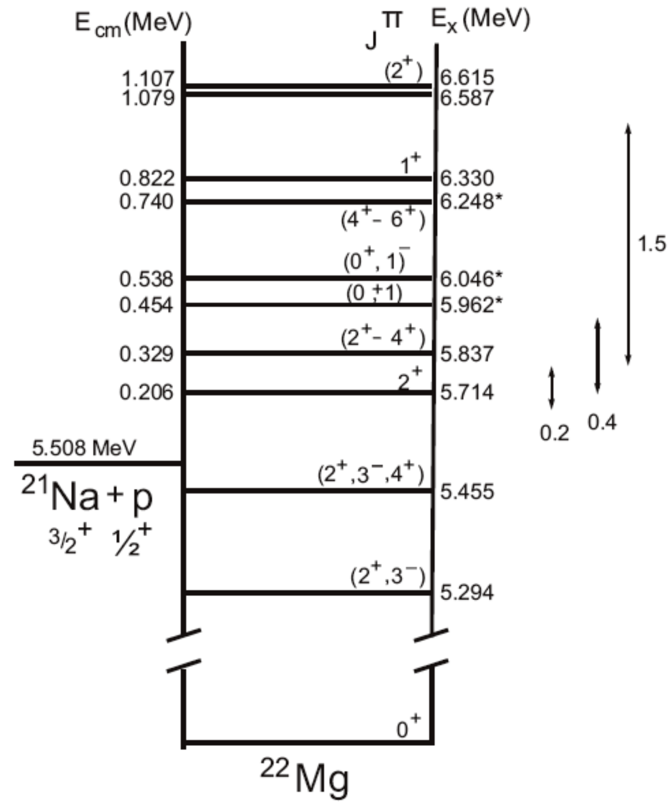




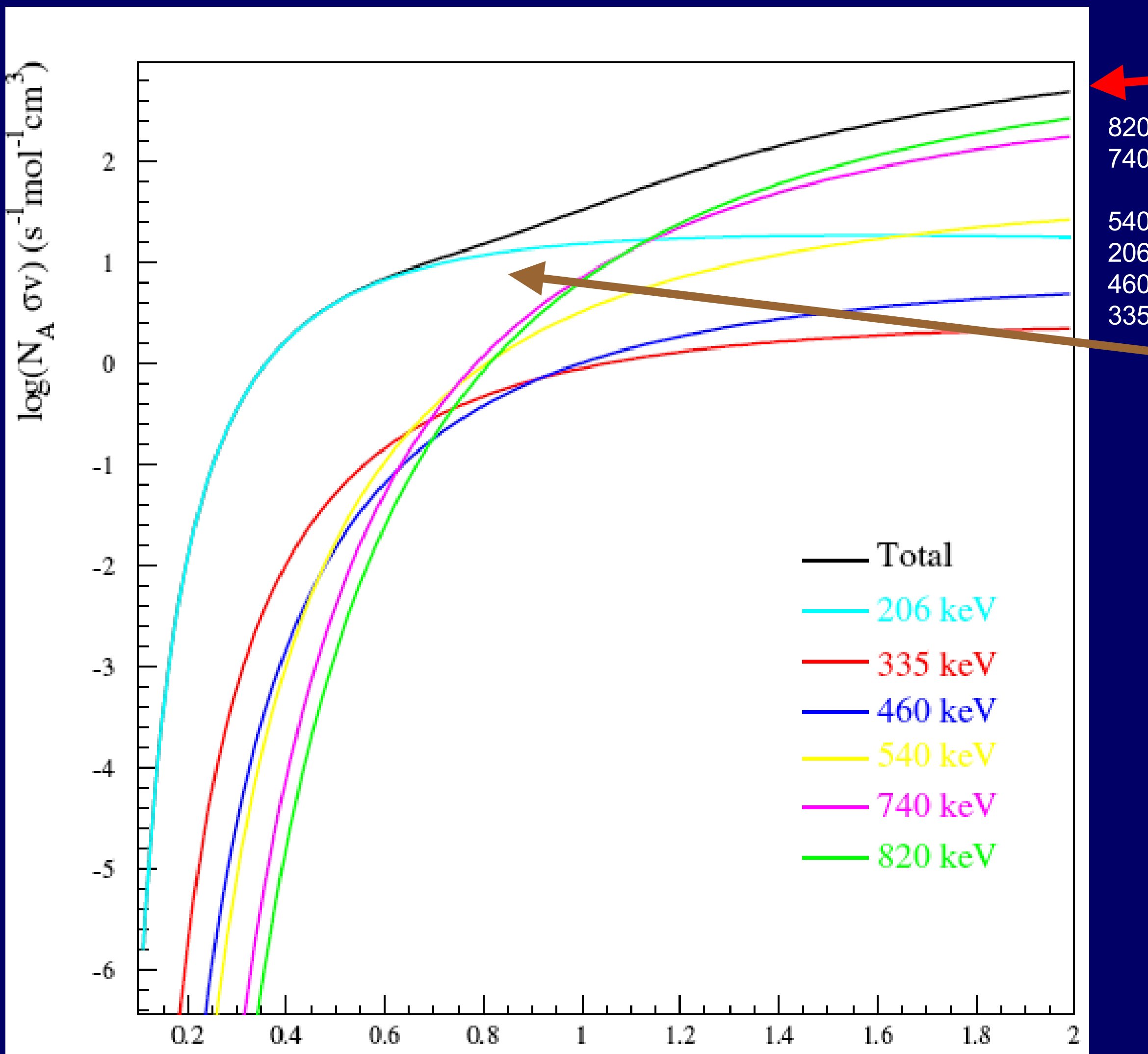
Summary Report on E824

$^{21}Na(p,\gamma)^{22}Mg$

- Received ^{21}Na beam ($\leq$ 2 x 10^9; ~600 epA)
- DRAGON operational
  - -used DSSSD as focal plane detector
  - -used beta activity, FC and elastics for flux
  - -used BGO gamma despite high γ bgd.
- Measured $\omega\gamma$, Γ for resonance at E_{cm}=822, 1107 keV
- Measured $\omega\gamma$ for resonance at E_{cm}=206 keV
- Measured new mass excess for ^{22}Mg
- Preliminary results ($\omega\gamma$) from other levels
  - \- E_{cm} = 329 keV ($\omega\gamma$ < 0.3 meV)
  - \- E_{cm} = 454 keV ($\omega\gamma$ ~ 1.2 meV)
  - \- E_{cm} = 538 keV ($\omega\gamma$ ~ 12 meV)
  - \- E_{cm} = 740 keV ($\omega\gamma$ ~ **219** meV)
  - \- E_{cm} = 822 keV ($\omega\gamma$ ~ **556** meV)
  - \- E_{cm} = 1107 keV ($\omega\gamma$ ~ 300 meV)

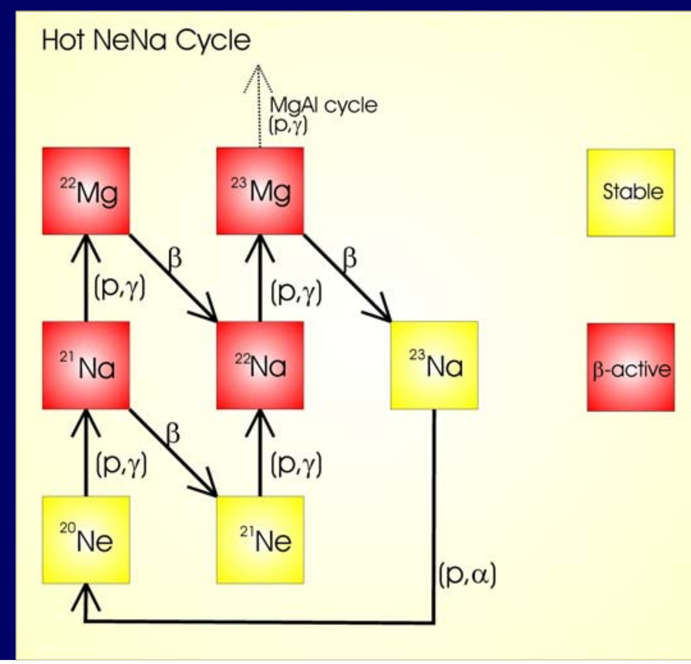


Stellar Rate – all ^{22}Mg levels



Sum of levels measured in this work.

Below 0.8 GK only the 206 keV resonance matters

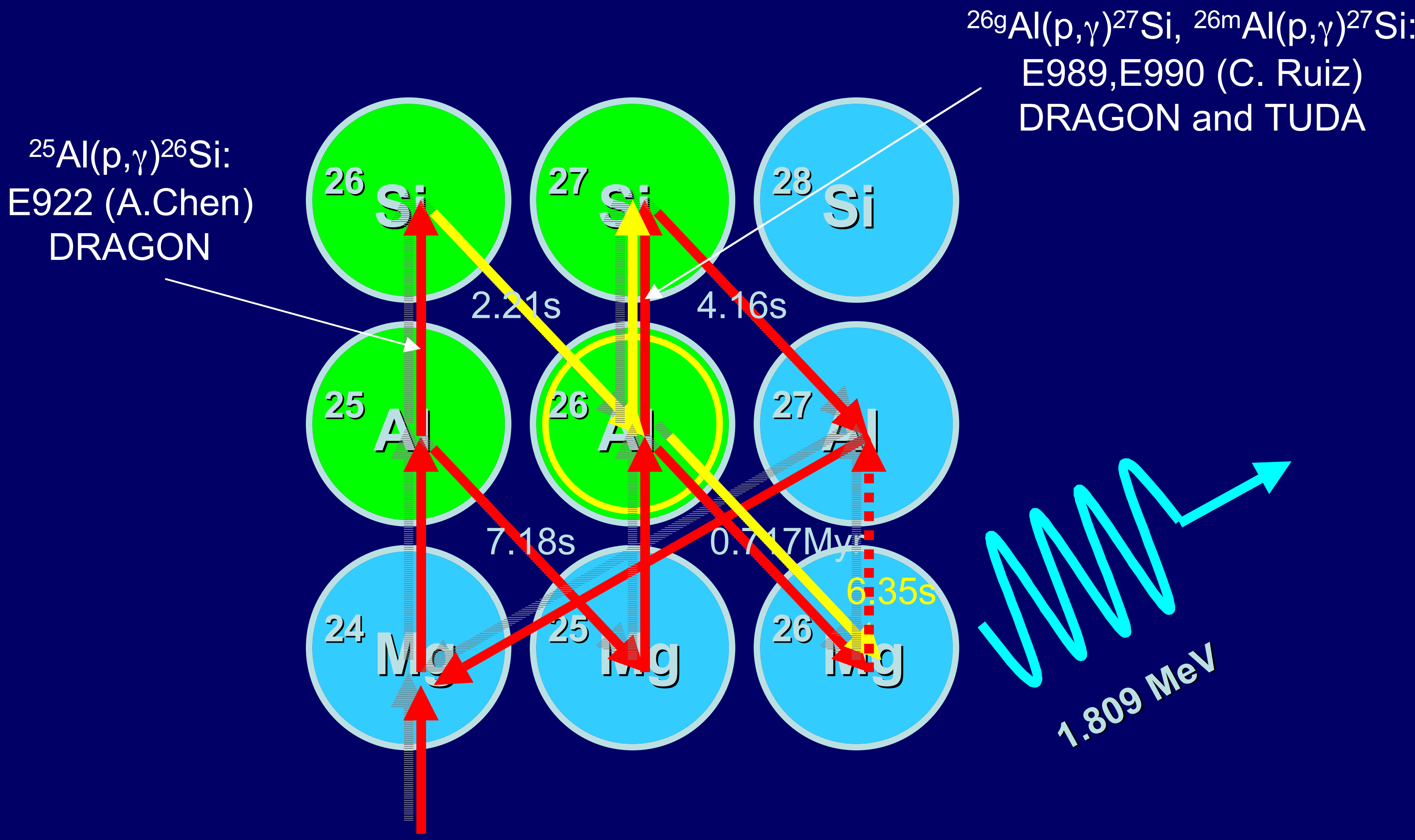


Opportunities for Surrogate Reactions

- Have we found all of the states that can contribute to a novae explosion? Probably, but….
- The state at 5.837 MeV has only been observed in one study and not confirmed in any other transfer reaction study or directly.
- Fortune et al discount this state as having any importance for the (p,γ) reaction as they support its assignment as a 3- state.
- There are ^{20}Na(^{3}He,p)^{22}Mg studies in progress at ISAC using TUDA.
- Studies in progress at HRIBF and ANL doing ^{12}C(^{12}C,2n) reactions to study gamma decay/measure branching ratios.

$^{26m,g}Al(p,\gamma)^{27}S$

MgAl cycle


$^{26g}Al(p,\gamma)^{27}Si$, $^{26m}Al(p,\gamma)^{27}Si$:
E989,E990 (C. Ruiz)
DRAGON and TUDA
$^{25}Al(p,\gamma)^{26}Si$:
E922 (A.Chen)
DRAGON
26 Si
27 Si
28 Si
25 Al
26 Al
27 Al
24 Mg
25 Mg
26 Mg
2.21s
4.16s
7.18s
0.717Myr
6.35s
1.809 MeV

Objectives

- E989 - DRAGON

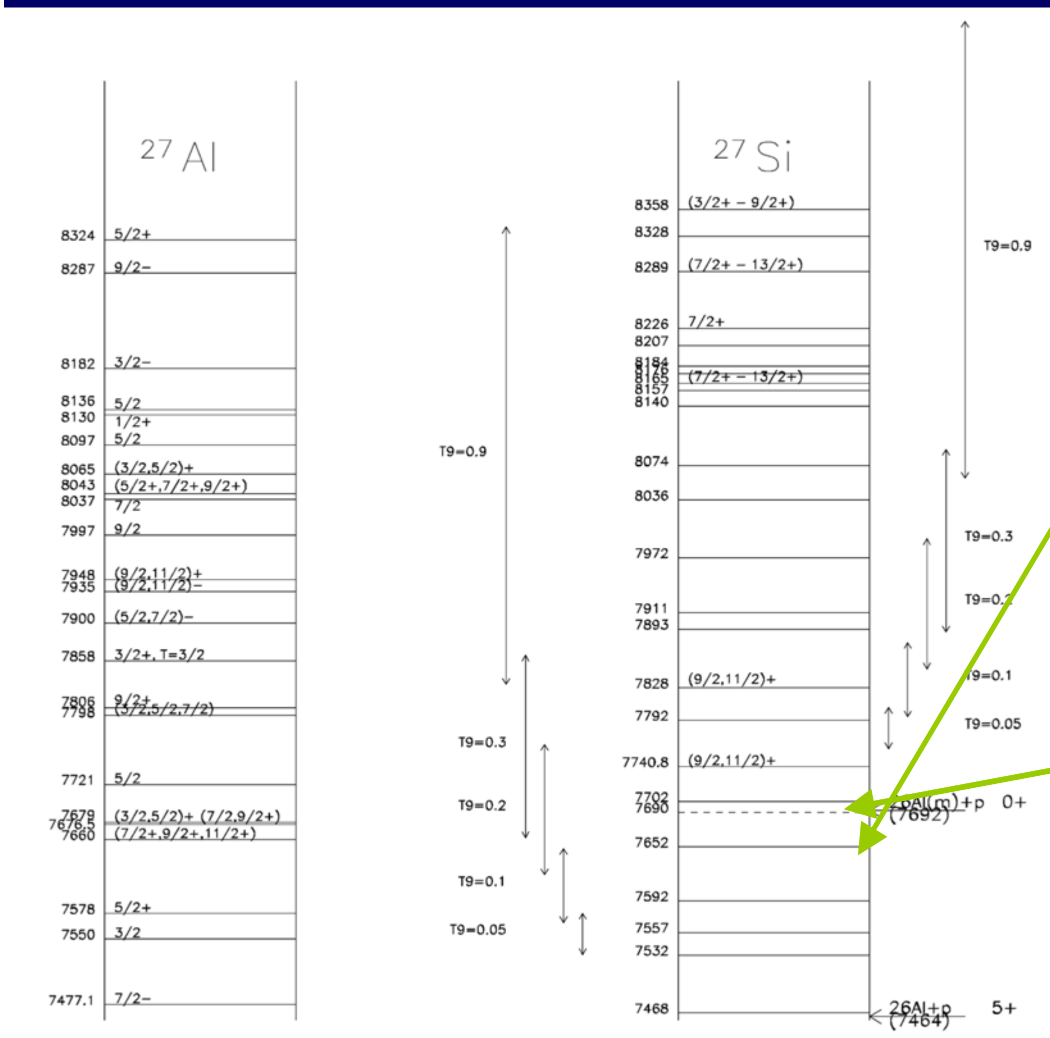
  Phase 1: Direct measurement of resonance strengths in $^{26g}Al(p,\gamma)^{27}Si$

  Phase 2: Direct measurement of resonance strengths in $^{26m}Al(p,\gamma)^{27}Si$ [isomeric beam]

- E990 - TUDA

  Identification of $^{26m}Al+p$ resonances in energy region relevant to SNII temperatures

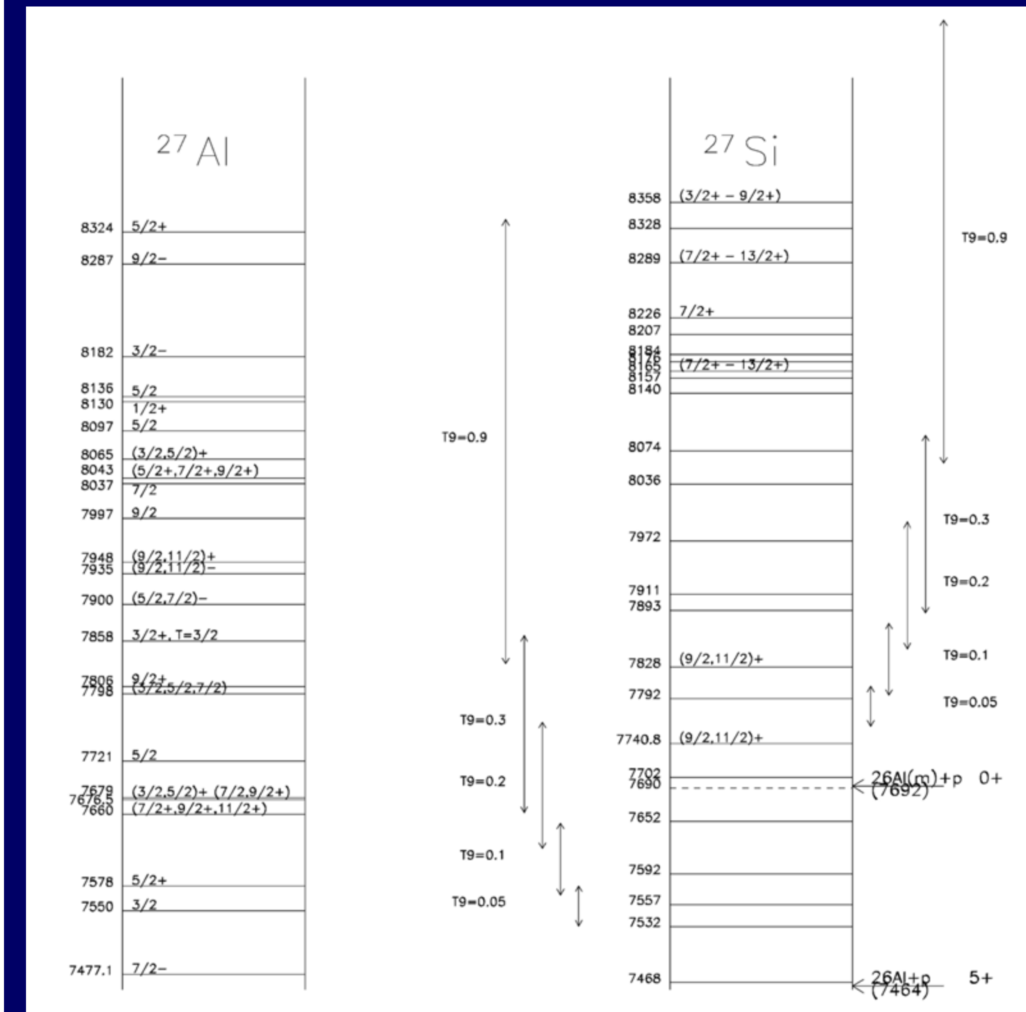
$^{26g}Al(p,\gamma)^{27}Si$



- ^{26g}Al (5^+) can only form high J states in ^{27}Si via low-energy radiative capture
- Several resonances below E_{cm}=900 keV contribute for $T_9 \leq 0.35$ Novae burning
- Most recent work* includes 18 resonances: dominant resonance is E_R=188 keV _ E_x=7652 keV
- Calculations for ONe WD Novae (J. Jose) show factor 2 change in final ^{26}Al for 30% variation in resonance strength
- Previous adopted value of $\omega\gamma$
- (0.064 μeV) based on exp. limits from transfer reactions
- Resonance at 226 keV for which no experimental info exists

*Iliadis *et al*. Astr. J. Sup. 134: 151-171 (2001)

$^{26m}Al(p,\gamma)^{27}Si$



- ^{26m}Al (0^+) can only form low J states in ^{27}Si via low-energy radiative capture
- At low T, several candidate states for resonance eliminated due to strong ^{26g}Al+p channel
- Calculations show low T ONe WD burning does not depend strongly on $^{26m}Al(p,\gamma)^{27}Si$: only final ^{26}Mg affected by changes in rate
- Isomeric state rate solely based on Hauser-Feshbach calculations; no experimental measurement exists
- At energies relevant to SNII, several candidate low-spin states not observed in ^{26g}Al+p channel – could contribute strong resonances to $^{26m}Al(p,\gamma)^{27}Si$

$^{26g}Al(p,\gamma)^{27}Si$ resonance properties

Excitation Energy (keV)	Resonance Energy (keV)	Resonance Strength	Total Width	Estimated Yield*
7652	188	0.064 meV	-	0.4×10^{-12}
7690	226	-	-	0.3×10^{-13}

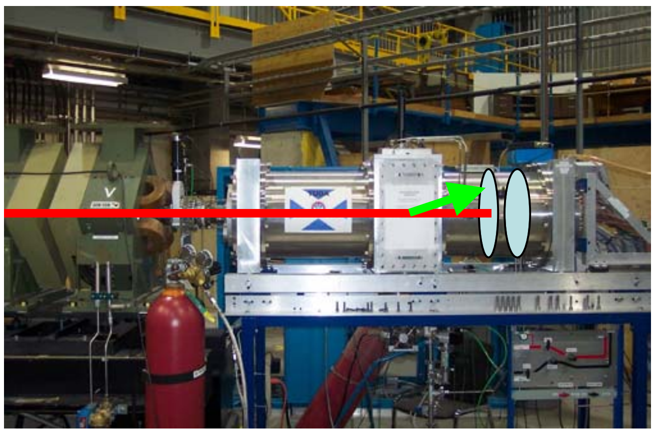
- With 10^9 ^{26}Al ions/sec, estimated count rate 0.23 cts/hr for 188 keV resonance for coincident γ-HI events
- Can achieve 15% accuracy in measurement of resonance strength with 10 days running
- Aim to achieve upper limit on 226 keV resonance strength

*reactions per incoming ion, calculated for 4 Torr H_2 Target (SRIM 2003 calculated stopping powers were used)

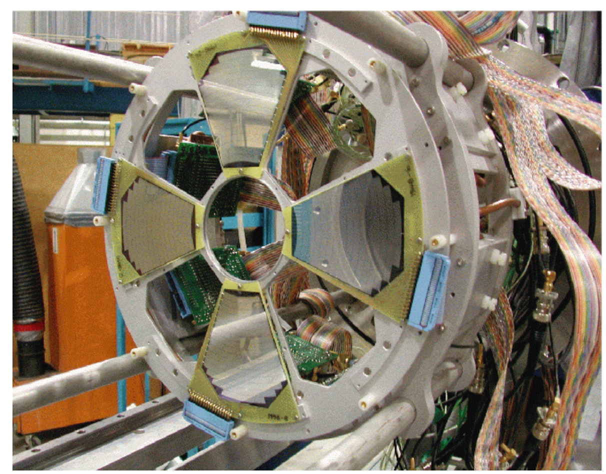
Opportunities for Surrogate Reactions

- Experiments performed or in progress at Yale using the $^{27}Al(^{3}He,t)^{27}Si(p)^{26}Al$ reaction or $^{29}Si(^{3}He,^{6}He)^{26}Si$ at energies for SN.
- Experiments proposed at ISAC using TUDA to perform elastic scattering studies using ^{26m}Al beam to map out properties of key states.

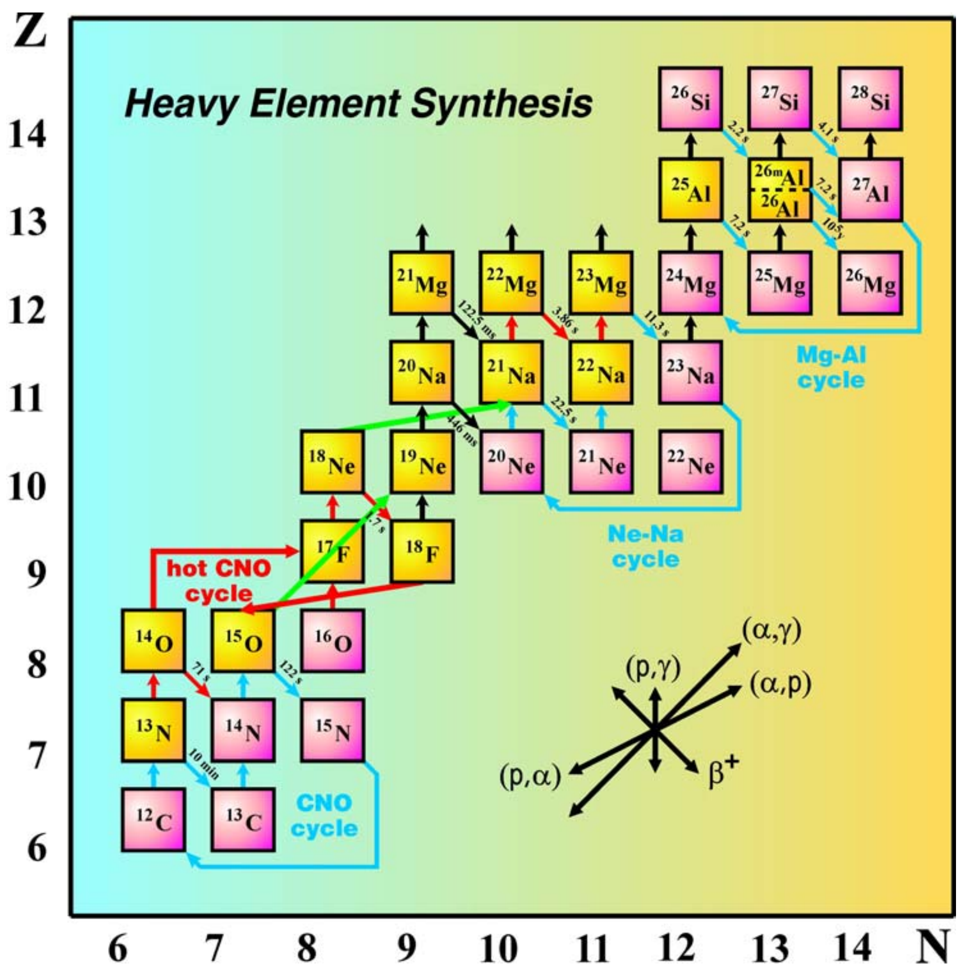
Identification of ^{26m}Al+p resonances using resonant elastic scattering



- TUDA – charged particle detector facility utilizing large solid angle, highly segmented silicon arrays
- 512 channel VME based acquisition system
- “Thick” (50-250 μg/cm^2) CH_2 targets
- Recoil protons detected at forward lab angles
- Extremely good angular and energy resolution



$^{15}O(\alpha,\gamma)^{19}Ne$



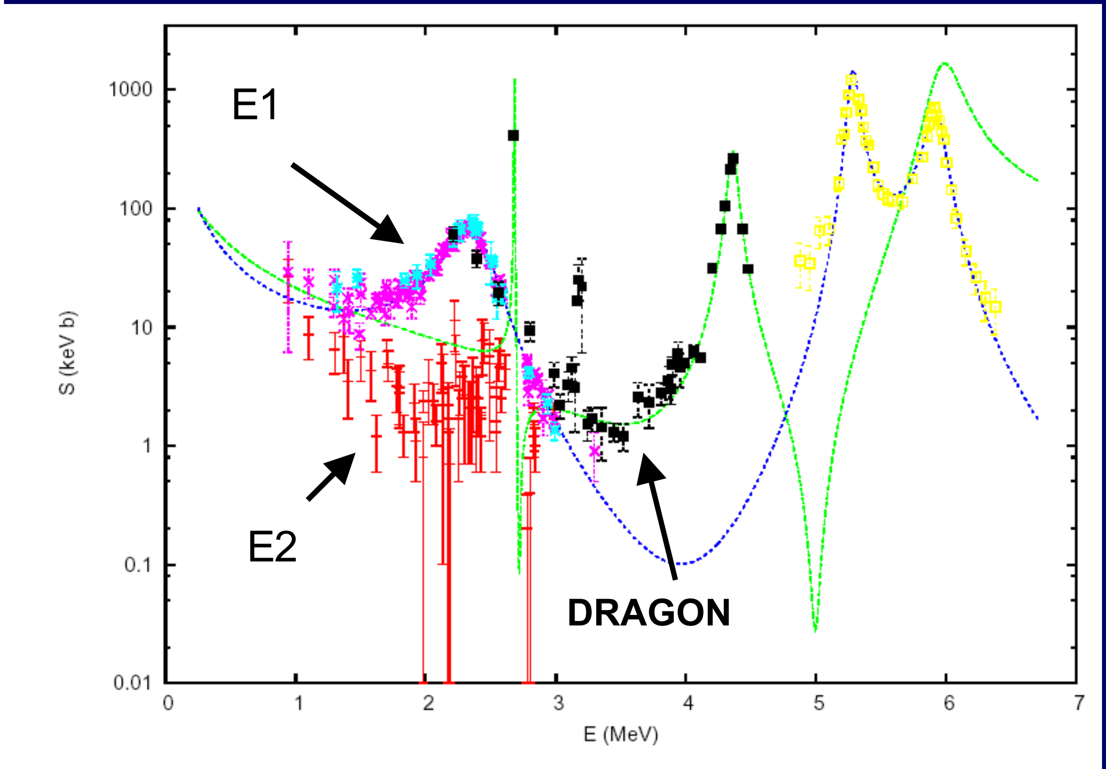
- Is there Hot CNO breakout in nova?
- At what temp. does breakout occur?
- What will it take to measure $\omega\gamma$?

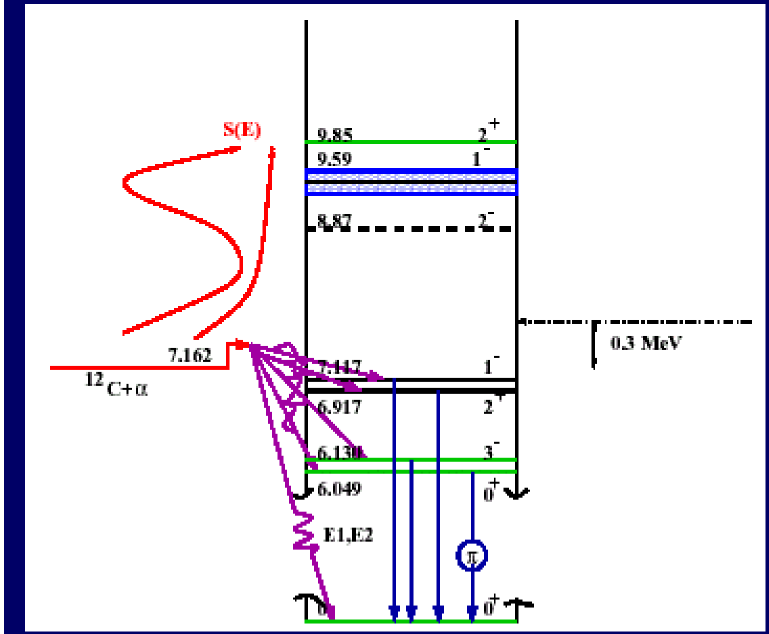
- Key state at E_x = 4.033 MeV;
  E_{cm}= 504 keV; E_b = 154 keV/u

- $\omega\gamma$ < 20 μeV; Yield < 1 c/h for 10^{11}/s

- Recent studies indicate not important

Studies of $^{12}C(\alpha,\gamma)^{16}O$
E952





- Considered very important reaction in elemental synthesis
- Has been studied for over 30 years but still key questions
- Difficult experiment to do using present layout of DRAGON

Planned DRAGON Experiments

Radioactive Beams

$^{19}Ne(p,\gamma)^{20}Na$ E811 hot CNO breakout; rp process; ECR
$^{13}N(p,\gamma)^{14}O$ DC E805 cold CNO breakout; ECR source,
$^{17}F(p,\gamma)^{18}Ne$ E946 hot CNO breakout; ECR source
$^{11}C(p,\gamma)^{12}N$ E983 hot pp chain (DC + Res.); ECR
$^{25}Al(p,\gamma)^{26}Si$ E922 rp process; ^{26}Al production; laser
$^{26m,g}Al(p,\gamma)^{27}Si$ E989 rp process; ^{26}Al production; laser
$^{15}O(\alpha,\gamma)^{19}Ne$ E813 hot CNO breakout; x-ray burst
$^{30}P(p,\gamma)^{31}S$ nova mechanisms; rp process

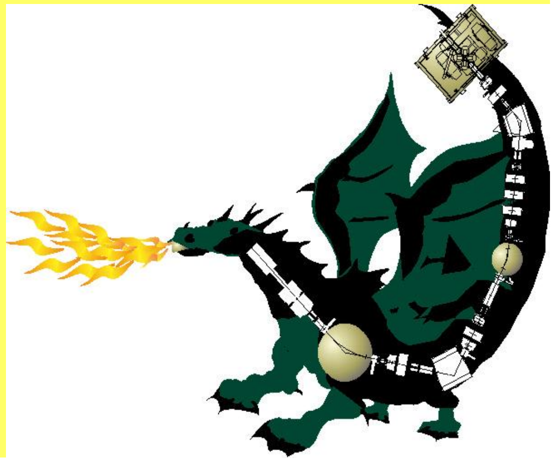
approved experiments   presented in Dec. 03

'ISAC II' Experiments (using Charge State Booster for A>30)

$^{34}Ar(p,\gamma)^{35}K$ rp process; ECR ion source
$^{56}Ni(p,\gamma)^{57}Cu$ rp process; laser ion source
$^{57}Cu(p,\gamma)^{58}Zn$ rp process; laser ion source

Stable Beam Studies

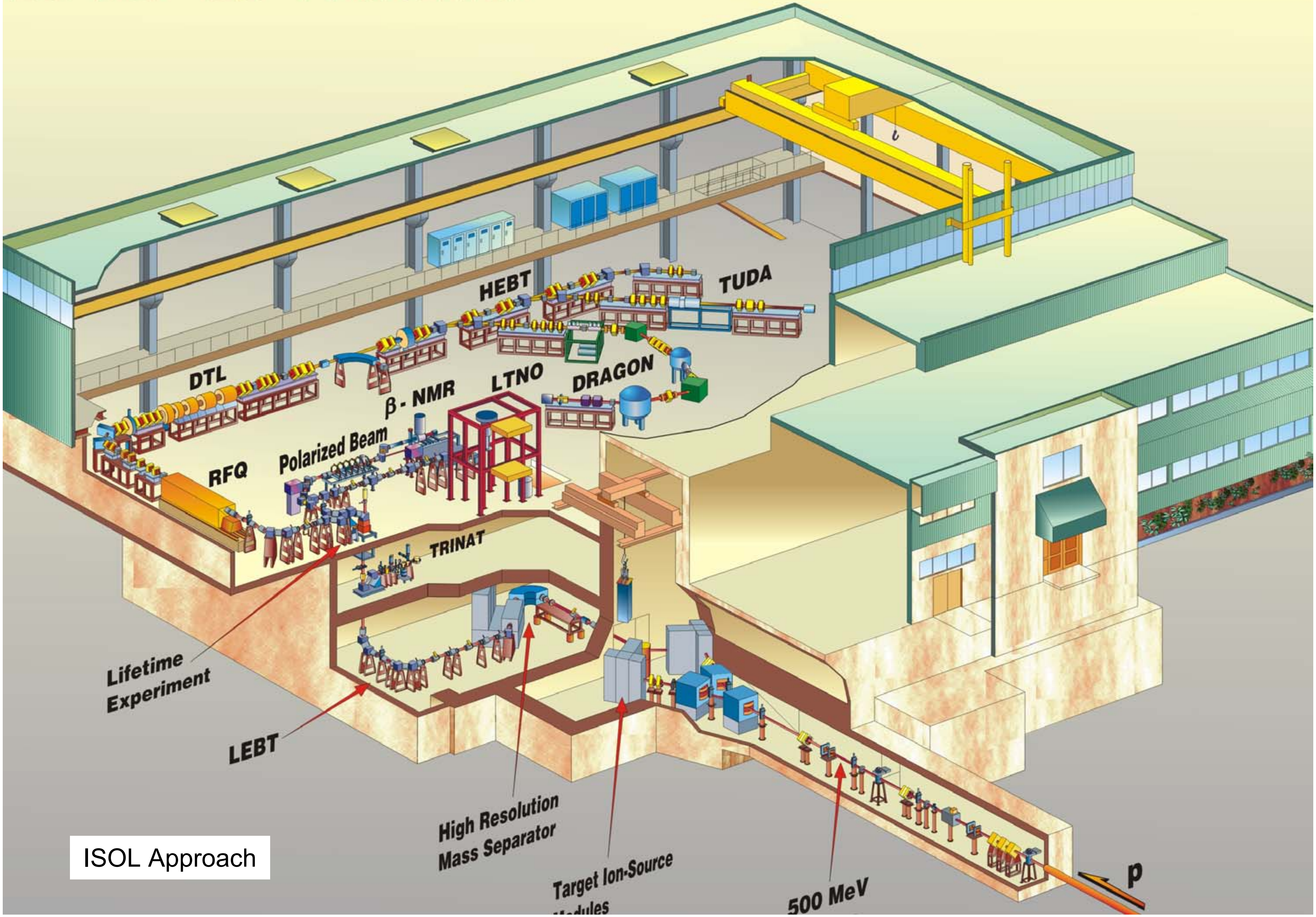
$^{12}C(\alpha,\gamma)^{16}O$ E952 helium burning; very important rx.
$^{12}C(^{12}C,\gamma)^{24}Mg$ E947 carbon burning; very difficult study



Capabilities of Present RB Facilities
for Radiative Capture Reactions

- ISAC (with DRAGON and TUDA)
- Louvain-la-Neuve (with ARES)
- SPIRAL
- HRIBF (with DRS)
- REX-ISOLDE
- PF (NSCL, GSI, RIKEN)
- RIA or EURISOL ???

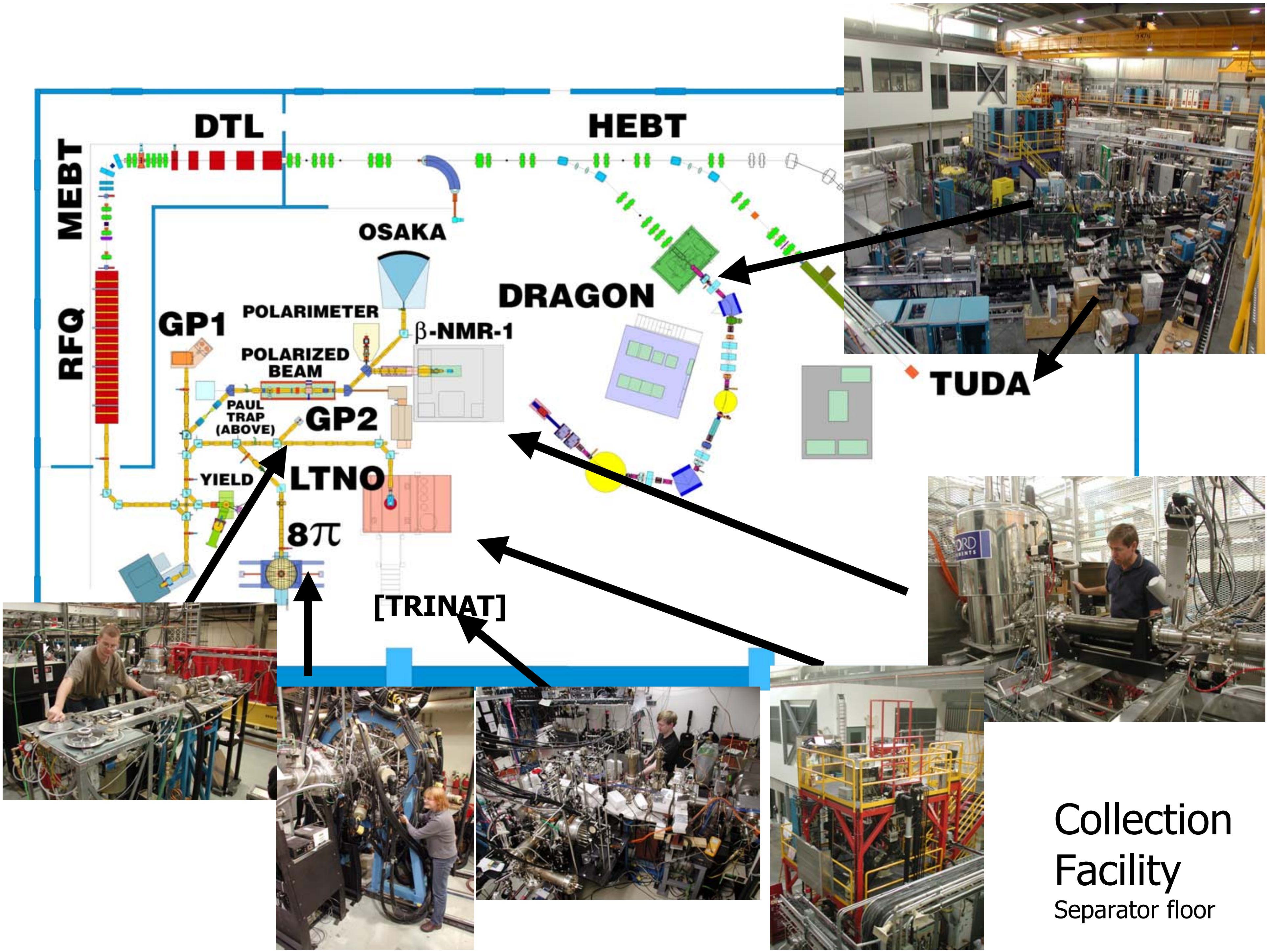
ISAC at TRIUMF



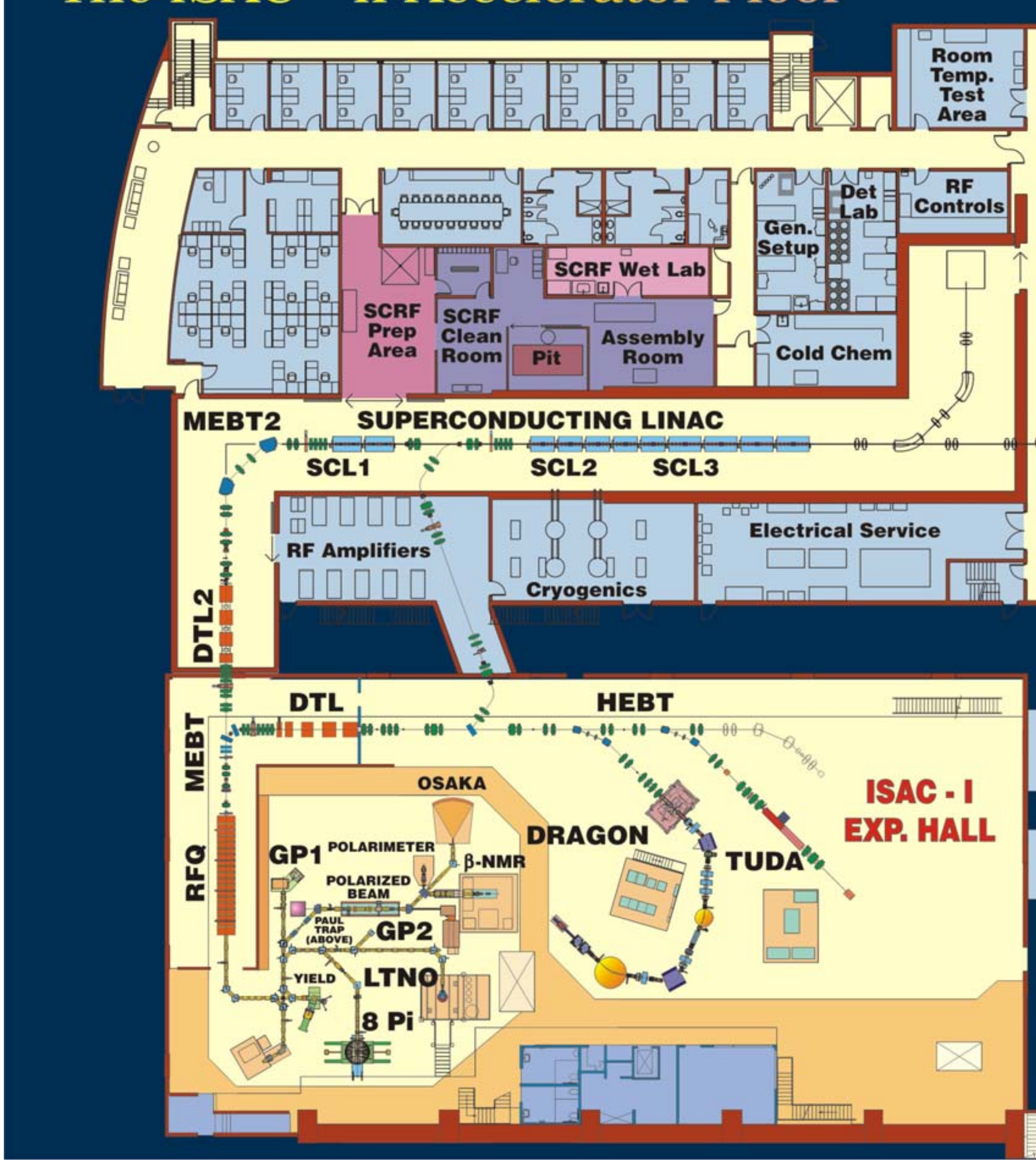
ISOL Approach

Collection Facility

Separator floor



The ISAC - II Accelerator Floor



E(RB)>Coulomb barrier

A < 150 u

Facilities for surrogate reactions, e.g., EMMA, TUDA II, TIGRESS

First beam in 2005

Radioactive Beams at TRIUMF

The ISOL Method

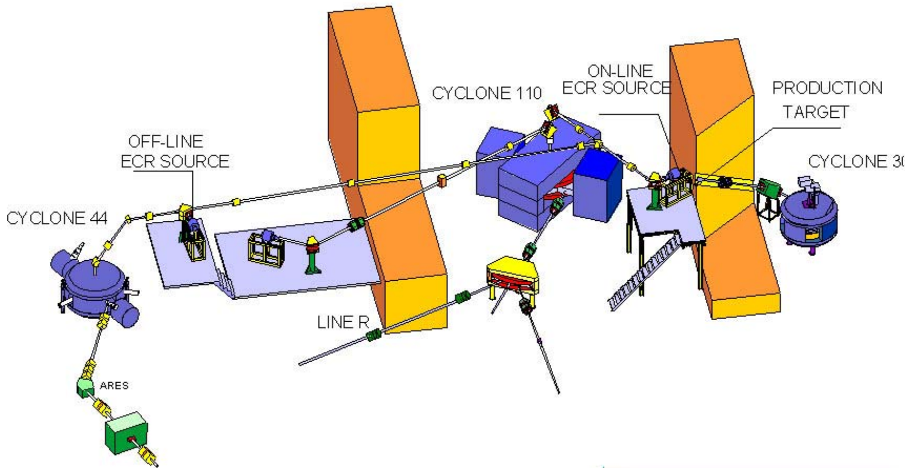
M. Dombsky TRIUMF
www.triumf.ca/people/marik/

- 500 MeV protons onto thick target
- Have used Nb, Ta, SiC, TiC, CaO, $CaZrO_3$, (ZrC)
- Intensities up to 100 μA possible (now 45 μA)
- Products diffuse out at high temperatures
- Species ionized in surface ion source;
  ECR (2003-it works but); Laser(2004)

Some Beam Intensities at Yield Station

^{8}Li	(Ta)	8×10^{8} pps
^{11}Li	(Ta)	2×10^{4} pps
^{21}Na	(SiC)	9.9×10^{9} pps
^{74}Rb	(Nb)	1.3×10^{4} pps
^{79}Rb	(Nb)	4.6×10^{9} pps
^{160}Yb	(Ta)	8.4×10^{9} pps

Louvain-la-Neuve



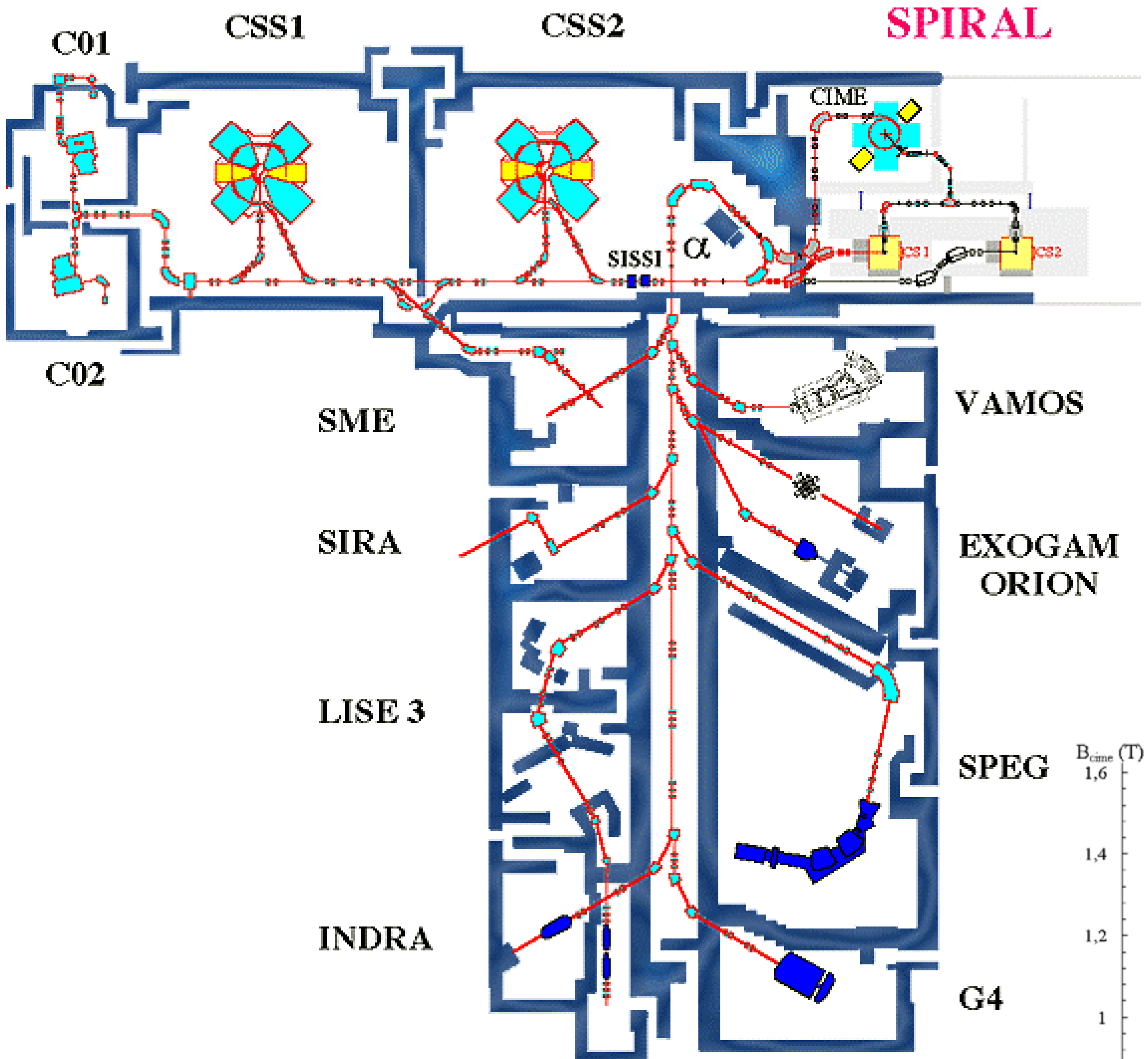
ARES Recoil Facility

Radioactive Beams available at CYCLONE and CYCLONE44

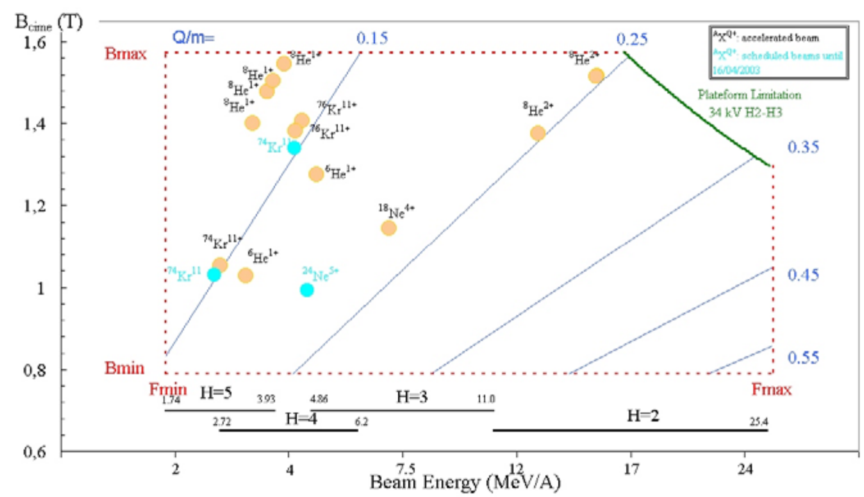
Currently available (as of September 2002) Radioactive Ion Beams at Louvain-la-Neuve.
The different available charge states with their respective typical **measured** intensities **after acceleration and separation** and energy range are given.
Note that the listed beams and charge states do not represent the limitations at our facility but show what has actually been produced and measured.

Element	***$T_{1/2}$***	***q***	***Intensity [pps]***	***Energy range [MeV]***
^{6}Helium	0.8 s	1+ 2+	$9 \cdot 10^{6}$ $3 \cdot 10^{5}$	5.3 - 18 30 - 73
^{7}Beryllium	53 days	1+ 2+	$2 \cdot 10^{7}$ $4 \cdot 10^{6}$	5.3 - 12.9 25 - 62
^{10}Carbon	*19.3 s*	*1+* *2+*	*$2 \cdot 10^{5}$* *$1 \cdot 10$*[redacted]	*5.6 - 11* *24 - 44*
^{11}Carbon	20 min	1+	$1 \cdot 10^{7}$	6.2 - 10
^{13}Nitrogen	10 min	1+ 2+ 3+	$4 \cdot 10^{8}$ $3 \cdot 10^{8}$ $1 \cdot 10^{8}$	7.3 - 8.5 11 - 34 45 - 70
^{15}Oxygen	2 min	2+	*$6 \cdot 10^{7}$* *$1 \cdot 10$*[redacted]	10 - 29 6 - 10.5 *
^{18}Fluorine	110 min	2+	$5 \cdot 10^{6}$	11 - 24
^{18}Neon	1.7 s	2+ 3+	$6 \cdot 10^{6}$ $4 \cdot 10^{6}$	11 - 24 24 - 33,45 - 55
^{19}Neon	17 s	2+ 2+ 3+ 4+	$2 \cdot 10^{9}$ *$5 \cdot 10^{9}$* $1.5 \cdot 10^{9}$ $8 \cdot 10^{8}$	11 - 23 *7.5 - 9.5 ** 23 - 35,45 - 50 60 - 93
^{35}Argon	1.8 s	3+ 5+	$2 \cdot 10^{6}$ $1 \cdot 10^{5}$	20 - 28 50 - 79

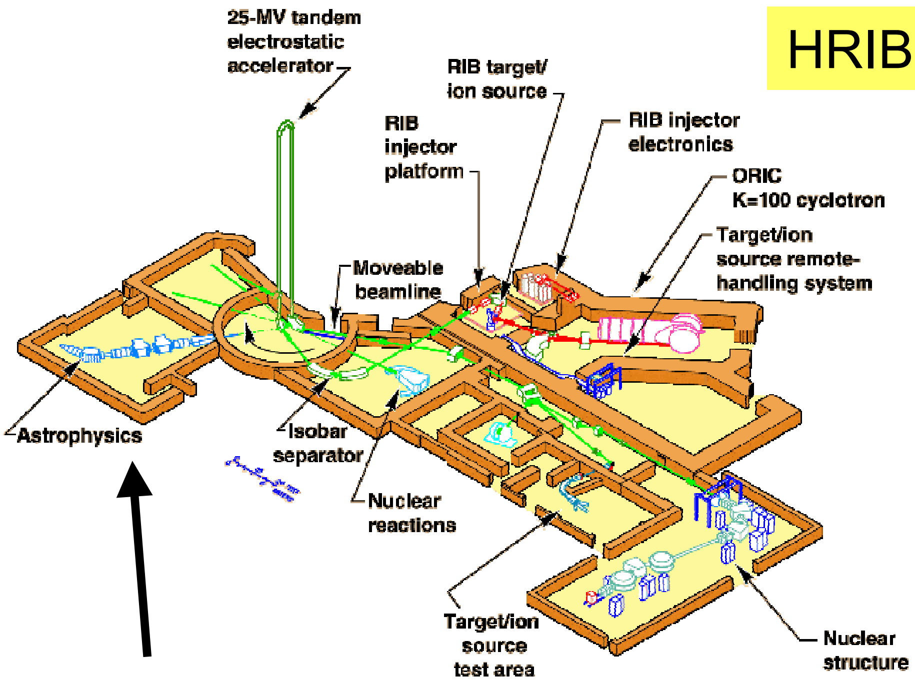
SPIRAL at GANIL

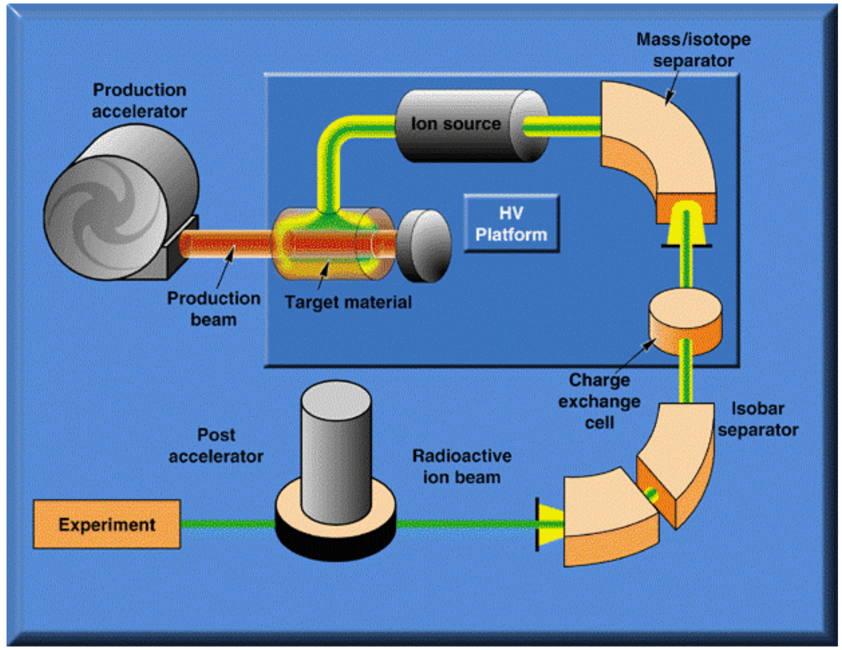


Overview
- -RB produced by projectile fragmentation/re-acceleration
- -ECR source used to ionize
- -Injected into CIME cyclotron
- -Beams limited to gases
- -Beam energy 1.7 – 25 MeV/u



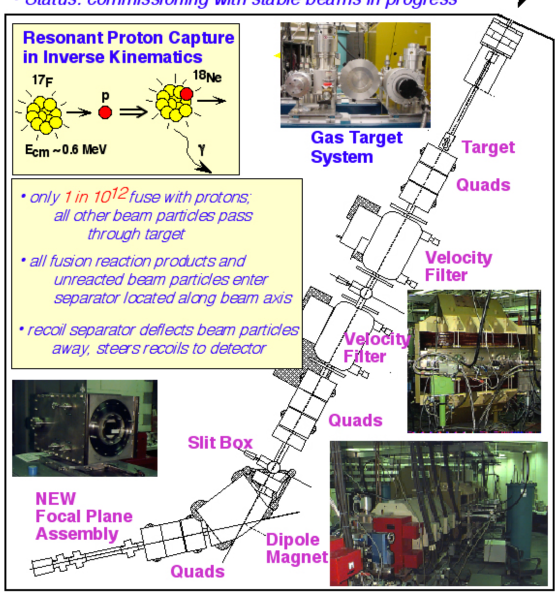
HRIBF





HRIBF Daresbury Recoil Separator

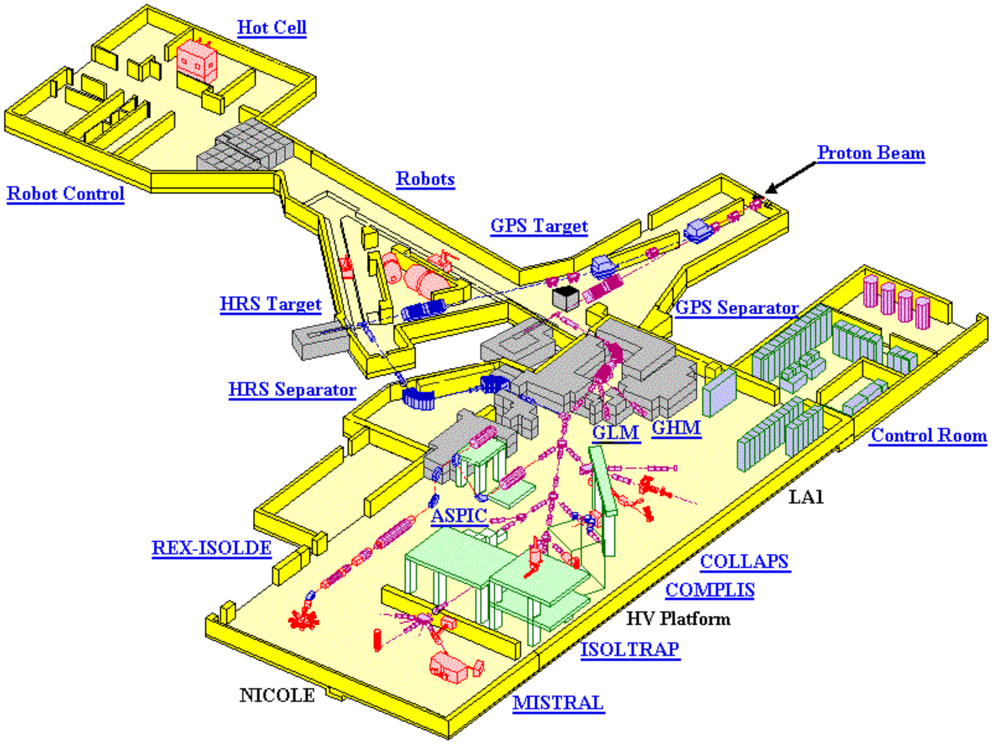
- Utilization: measurement of capture reactions such as $^{7}Be(p,\gamma)^{8}B$ and $^{17}F(p,\gamma)^{18}Ne$
- Status: commissioning with stable beams in progress

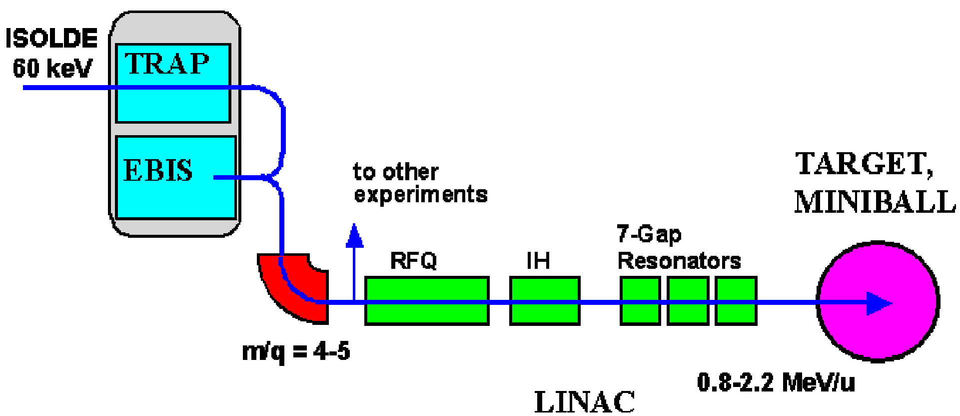


Radioactive Isotopes	Energy (MeV) Range Accelerated to Date	Ion Source/Charge Exchange Cell or Batch mode cycle	Ions/Second From the Platform[1]
^{11}C	predicted values at this time	BATCH/ 40 min	8x10^{5} [2]
^{17}F	10.5-170	KENIS/No EBPIS/Yes	6x10^{7}
^{18}F	10.5-14	KENIS/No	1x10^{7}
^{18}F	predicted values at this time	BATCH/ 4 hr	1x10^{8} [2]
^{56}Co[3]	predicted values at this time	BATCH/ 5 day	4x10^{9} [2]
^{56}Ni[3]	predicted values at this time	BATCH/ 5 day	2x10^{8} [2]
^{69}As	160	Liquid metal EBPIS/Yes	1x10^{7}
^{67}Ga	160	Liquid metal EBPIS/Yes	1x10^{6}

[1]Actual beam on target depends on charge state fraction and transport efficiency. Rule of thumb is 5-10% of what comes off the platform is delivered to the target.
[2]Intensities given are at the start of each cycle and will decrease during the cycle according to the halflife.
[3]Isobaric separation of ^{56}Co and ^{56}Ni will not be possible.

REX-ISOLDE at CERN-ISOLDE





	H																	He
	Li	Be												B	C	N	O	F	Ne
	Na	Mg												Al	Si	P	S	Cl	Ar
	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
	Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
	Fr	Ra	Ac															
LANTHANIDES				Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
ACTINIDES				Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	

Concluding Remarks

- Radiative capture reactions are important for furthering our understanding of explosive stellar scenario.
- Rates of reactions involving radioactive reactants are generally unknown and difficult to measure directly.
- Program in progress at ISAC using DRAGON and elsewhere.
- Regardless, there exist many opportunities for surrogate reactions using both stable and radioactive heavy ion beams.

The DRAGON Collaboration before 2004

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